

AD No. 27387
ASTIA FILE COPY

SYNTHETIC LUBRICANTS FOR GYROSCOPES

J. B. Romans and T. M. Thomas

Surface Chemistry Branch
Chemistry Division

February 4, 1954

IMPORTANT NOTICE

This document contains an evaluation of a commercial product by the Naval Research Laboratory and is not to be considered as an official endorsement or disapproval of that product by the Navy Department. It is made available as an official Naval Research Laboratory publication with the understanding that the information contained therein will not be released for publication nor disclosure to any unauthorized person who is not in the employ of the Department of Defense.



NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

| | |
|------------------------------|----|
| Abstract | iv |
| Problem Status | v |
| Authorization | v |
| INTRODUCTION | 1 |
| EXPERIMENTAL WORK AT NRL | 2 |
| Gyros and Lubricants Studied | 2 |
| Methods Used | 4 |
| Gun Sight Mark 20 Gyros | 5 |
| Stable Element Mark 6 Gyro | 8 |
| Gun Sight Mark 15 Gyros | 15 |
| Power Supply Equipment | 23 |
| Gunar Mark 31 0.1 Fg 2 Gyros | 24 |
| CONCLUSIONS | 32 |
| RECOMMENDATIONS | 35 |
| ACKNOWLEDGMENT | 37 |
| REFERENCES | 38 |

ABSTRACT

The failure of many types of Naval gyroscopes while in service or after being taken from storage has been due to rotor bearing failures. A project was established to develop improved lubricants for Naval gyroscopes and to reduce the number of proprietary lubricants to one or two.

The Naval gyroscopes investigated included those from the electrically driven Gun Sight Mark 20 and Stable Element Mark 6, the air-driven gyros from the Gun Sight Mark 15 and the Gunar Mark 31 0.1 Fg 2 gyro. Measurements were made of bearing temperatures, rotor speed, rate of deceleration, power input, and bearing noise level; and the noise components were analyzed.

Both Specification 14-0-20 oil and MIL-G-15793 instrument grease adequately lubricated the two Gun Sight Mark 20 gyros. These lubricants were also suitable for the Stable Element Mark 6 gyro, but satisfactory use of the oil required that the level in the lower reservoir be higher than that required for the proprietary lubricant.

Gyros from the three Gun Sights Mark 15 were operated with Specification 14-0-20 oil, MIL-G-15793 instrument grease, and an experimental copper phthalocyanine-diester grease. The 14-0-20 oil and the instrument grease provided adequate lubrication for operation of these gyros. After a period of storage following the tests, the oil-lubricated elevation gyro bearings were rather dry while those lubricated with the greases were well protected against corrosion.

The instrument grease MIL-G-15793 was found to be the most suitable of the lubricants studied and is recommended for use in shielded bearings. The use of bearings of this type insures proper retention of the lubricant and provides a certain amount of protection during equipment overhaul but requires greater care by the bearing manufacturer in inspection and handling of bearings and lubricant.

Satisfactory operation of the Air Supply units used to drive the Gun Sights Mark 15 will require the use of a high temperature grease of the MIL-L-3545 type in the connecting-rod ball bearings.

Operation of one of the Gunar Mark 31 gyros with Teresso V-78 petroleum oil was continued for 10,000 hours although very serious changes in operating characteristics had occurred at about 2500 hours. Two gyros failed to operate after 1600 and 1080 hours, respectively, when Specification (ORD) 14-0-20 oil was used. The use of antiwear agents and of less volatile components in the 14-0-20 oil is evidently needed. The possibility of employing MIL-G-15793 grease for the Gunar gyros should be investigated.

NAVAL RESEARCH LABORATORY

The sound-level meter and Panoramic Sonic analyzer were found to be useful tools in obtaining bearing noise data and are recommended for use in rotor bearing inspection during overhaul of equipment. While studies of the bearing noise spectra revealed that the principal noise peaks were characteristic resonant vibrations of the gyro structure, these spectra reflected general changes in bearing condition. The spectra were frequently found to cover almost the entire audio frequency range, thus requiring the use of vibration pickups with wide frequency response characteristics.

PROBLEM STATUS

This is a final report on this phase of this problem. Work is continuing on other phases.

AUTHORIZATION

NRL Problem C02-13
RDB Project ND 461-210
Bureau # NRL-46-Relb-519-3

Manuscript submitted November 30, 1953

SYNTHETIC LUBRICANTS FOR GYROSCOPES

INTRODUCTION

Wartime experiences of the Navy revealed that unsatisfactory operation of certain types of naval ordnance equipment could very frequently be traced to failure of the gyroscope rotor bearings. This often occurred after a comparatively short period of service. Equipment removed from storage often failed shortly after being placed into use. Because of the limited information available from equipment manufacturers (1, 2) and from the services (3) relating to the gyro rotor bearing failures encountered by the Navy, it has been necessary to obtain more specific data relative to normal bearing behavior and to attempt to determine the most common causes of failure. Therefore, a study of the influence of mechanical design, quality of bearings, suitability of the lubricant, and the relation of bearing noise to bearing quality, life, and proper lubrication has been made.

In order to simplify the procurement and requisitioning of gyro lubricants, it is desired by the Bureau of Ordnance that the approximately fifteen proprietary lubricants be reduced to one or two. To accomplish this, the function of the lubricant in high speed ball bearings has been studied under both moderate and extreme operating conditions.

Certain advantages of grease over that of oil for the lubrication of gyroscope rotor bearings should be recognized. Experience has shown (1, 2, 4, 5) that during long periods of instrument storage, oil tends to evaporate and drain away from the bearing surfaces thereby inviting early failure when the equipment is placed in service. A grease which has been well fortified against oxidation and excessive loss of lubricating fluid will be retained in the bearings for long periods of storage. These advantages have resulted in considerable recent industrial emphasis on this class of lubricant.

In addition to difficulties encountered with ordnance equipment in current use, the recent development of new gyroscopic instruments operating at more extreme temperatures and much higher speeds has resulted in increasingly stringent lubrication requirements. Lubricants used prior to this investigation have not been satisfactory for use under these extreme conditions. The gyro manufacturers have not been in a position to develop new lubricants or to do extensive testing (1, 6).

The first phase of the study of gyroscope lubrication by this Laboratory (7, 8) included a survey of various equipment manufacturers and Naval repair stations in order to learn current practices concerning lubrication, bearing quality standards, and other pertinent information. It was revealed that the paramount problem in overhaul work was that of obtaining suitable replacement bearings. In order to facilitate the development of improved gyroscope lubricants, typical gyros were operated with the lubricants specified by the manufacturer. Not all of these lubricants proved to be satisfactory. At the time the first phase of the work was completed, two gun sight gyroscopes were still operating on a diester-type oil and a diester-type grease each of which is available under Navy or Military specifications.

The satisfactory operation of some of the gyros on the proprietary lubricants and information obtained at several overhaul shops, has led to the conclusion that many bearing failures reported by the service were due to inferior replacement bearings, poor overhaul technique, and careless handling of equipment (7, 8).

Success of the diester lubricants indicated the advisability of extending the study of these and other lubricants in other types of Naval gyroscopes. It was also desired to expand the investigation of the relation of bearing noise phenomena to bearing life and quality by obtaining noise spectra covering a wider frequency range. This required the use of vibration pickups responsive to the higher frequencies.

EXPERIMENTAL WORK AT NRL

Gyros and Lubricants Studied

Tests which were in progress on the Gun Sight Mark 20 gyros "C" and "D" at the time of writing the previous report (7, 8) were continued. In addition, several of the gyroscopes of the types used in the earlier studies were operated on synthetic diester-type lubricants. These included the 9000-rpm air-driven train and elevation gyros from three Sperry Gun Sights Mark 15, Mod 3, and one Arma Stable Element Mark 6 electric gyro which operated at about 8760 rpm. The air-driven train and elevation gyros from two of the Gun Sights Mark 15 were supplied in overhauled condition by the Naval Ordnance Plant, Indianapolis. The third set of air-driven gyros were from among those used in the previous work. These gyros were overhauled by the Norfolk Naval Shipyard at Portsmouth, Virginia.

In addition to studies made on lubricants for heavier shipboard gyros, it was desired by BuOrd that the problem of lubricating the small electrically driven Gunar Mark 31 0.1 Fg 2 gyro be investigated. Accordingly, three gyros of this type were made available for study.

Power for operating the Mark 20 gyros was supplied by the specified Motor-Generator Mark 5, Mod 0; while that for the Stable Element gyro was the Type MG-145 Motor-Generator. The air-supply units BuOrd No. 417054-1 were used for driving the Gun Sight Mark 15 gyros. An electronic 12 volt, 400 cycle, 3-phase power supply was used to drive the Gunar gyros at approximately 12,000 rpm.

All the gyros studied were equipped with Class ABEC-3 ball bearings with the exception of the gyros overhauled at the Norfolk Naval Shipyard and the Gunar gyros. Class ABEC-5 bearings had been purchased from the Sperry Gyroscope Company and were supplied to the Norfolk Naval Shipyard for use in the air-driven gyros overhauled by that activity. All the bearings used in the air-driven gyros were special New Departure R2 type with case-hardened retainers. Marlin-Rockwell R2 and R4 bearings equipped with nonmetallic retainers were used in the Gun Sight Mark 20 and Stable Element gyros, respectively. The Gunar gyros came equipped with precision Barden R-2H ball bearings with "Synthane" retainers. Unlike all the other gyros studied, the outer races of the Gunar gyros revolved around the stationary inner races. The rotor bearings of the Gun Sight Mark 20 gyros were preloaded by means of a Z-spring located in the cage-end bell housing of the gyro motor. Since the rotors of these gyros operated in a horizontal position, the amount of preload was the same on each bearing. Measurements made on the Z-springs indicated that the preload on the "C" gyro bearings was approximately 8-1/4 pounds while the spring in the "D" gyro exerted a force of 9 pounds, 10 ounces. The rotor and eddy current disc assembly used in the Gun Sight Mark 20 gyros weighed slightly over one pound. The Gun sight Mark 15 train gyros operated with the rotors in a horizontal position. Any preload on the bearings was determined when the bearings were adjusted at the time of overhaul and was governed by rotor coast time under

specified conditions. The elevation gyro rotors were identical to those of the train gyros except that they were mounted with the rotor axes in a vertical position. The bearings were adjusted to give a certain coast time at the time of overhaul. The lower bearing carried the weight of the 1-1/3 pound rotor. The heavy rotor of the Stable Element gyro weighed 20 pounds, 12 ounces and was mounted in the same position as the air-driven elevation gyro rotors. A Z-spring beneath the lower bearing exerted a force of 20 pounds, four ounces leaving the upper bearing very lightly loaded. The Gunar gyro rotors weighed 1.3 ounces and were mounted with the axes in a horizontal position. The bearings were preloaded between 1.5 and 2 pounds by means of differences in the thickness dimensions of spacers between the inner races and outer races of the two rotor bearings (9).

The Gun Sight Mark 20 gyro (C) was lubricated every 200 hours with Specification (ORD) 14-0-20 oil (10), while the companion gyro was lubricated with 0.10 gram of Specification MIL-G-15793 lithium soap grease (11) in each bearing. The grease was deposited directly on the bearing races by means of a No. 2YL "Yale B-D Lok-Syringe" equipped with a B-D 22 needle made by Becton, Dickinson and Company, Rutherford, N. J. The amount of grease placed in each bearing was determined by weighing the syringe on an analytical balance and using the method of "weighing by difference." The Stable Element gyro was first operated with Specification (ORD) 14-0-20 oil and lubricant was added every 60 hours. For the second test, new bearings were installed and lubricated with 0.45 gram of MIL-G-15793 grease placed in each bearing by using the hypodermic-type syringe mentioned earlier. The oil feed wick was removed from the upper bearing. The Gun Sight Mark 15 gyros were operated in three sets designated "C," "D," and "E," respectively, and consisted of one train and one elevation gyro in each set. All the gyros had been lubricated with Specification (ORD) 14-0-20 oil upon assembly. The gyros of set "C" were used as received from the overhaul shop. The rotor assemblies of sets "D" and "E" were dismantled and the bearings washed in solvent to remove excess diester oil. The bearings were not removed from the rotor shafts. The bearings in set "D" were lubricated by the addition of 0.020 gram of MIL-G-15793 grease in each bearing while those in set "E" were similarly lubricated with NRL experimental copper phthalocyanine grease containing a diester oil. The grease was added to the bearings by means of the syringe used for lubricating the Stable Element bearings. The felt oil pads were removed from the rotor bearing sleeves upon reassembly of the gyros. Except where specifically mentioned, none of the gyros used in the study were relubricated during the tests. The diester oil used was the same as that employed in making the greases, i.e., 14-0-20, and had a viscosity of 3.2 centistokes at 210°F.

The Gunar Mark 31 gyros, designated as C-31, C-32, and C-35, were lubricated at assembly by the manufacturer with Teresso V-78, a petroleum-type lubricant having a viscosity of approximately 15 centistokes at 210°F and containing an oiliness additive. The lubricant was introduced to the bearings before assembly by vacuum impregnation of the "Synthane" retainers (9). The gyros were designed to operate for 6000 to 10,000 hours in an atmosphere of helium at a temperature between 160°F and 175°F with no further lubrication other than that supplied by the oil-soaked bearing retainers (9).

After preliminary coast time studies (to be described later), the gyros designated as C-32 and C-35 were disassembled by removing the shaft and stator which left the bearings and spacers in place in the rotor. The bearings were washed in precipitation naphtha to remove excess lubricant. The rotor assemblies were placed in continuous extraction equipment with additional precipitation naphtha and extraction of the petroleum lubricant was carried on for four hours. The vacuum impregnation of the retainers with 14-0-20 oil was accomplished by suspending the C-32 rotor assembly over a quantity of the oil in a large suction flask and evacuating the flask to 0.35 mm pressure for 30 minutes at a temperature of 165°F. By tipping the flask, the rotor was immersed in the oil while the pressure was slowly raised. The C-35 rotor assembly was treated in the same way except the oil was heated to 300°F prior to immersion of the rotor.

Methods Used

Measurements were made of rotor speeds, rate of deceleration of the rotor, power input, bearing temperatures, and bearing noise level, the noise components being analyzed. With the exception of the Gunar gyros, rotor speeds in rpm were determined within 1/2 percent by means of a General Radio Strobotac calibrated daily. The deceleration rates on the Gun Sight Mark 20 gyros and the Gunar gyros were such that total coast times could be taken. However, the rate of deceleration of the air-driven gyros and the Stable Element gyro, defined as the time necessary for the rotor to decelerate 1000 rpm from operating speed, was obtained by means of the Strobotac and a stopwatch. In addition, measurements were also made of the time required for these rotors to come to a stop from 900 rpm. This was done in order to reduce the effect of windage at the higher rotor speeds. Similar measurements were also made on the Gunar gyros by substituting an oscilloscope for the Strobotac.

Power input of the electric gyros was measured by a Weston Model 310 single-phase wattmeter and a Weston Model 329 3-phase wattmeter; for the Gunar gyros a Model 102 VAW meter made by the John Fluke Engineering Company was found to be the most suitable.

The heavier electric gyros were operated in an ambient temperature of 70°F to 80°F with no additional heat being supplied to any of the units. The air-driven gyros were housed in cases which were maintained at approximately 140°F. The Gunar gyros were installed in small cases measuring 2 inches in diameter and 1-1/2 inches long. Each case was fitted with two admittance tubes and with glass seals carrying conductors for thermocouples and for power supply. These gyros were operated in an oven maintained at 170°F.

With the exception of the Gunar gyros, temperatures of all the bearings were measured by thermocouples placed directly on the outer races of each bearing. However, since the bearing outer races of the Gunar gyros were inaccessible, one thermocouple was placed under a small stainless steel clamp placed around the gripping ring adjacent to the rotor and located on the opposite end of the gyro from the stator. The temperature measured, therefore, was that of the average of the gyro assembly as determined at that point.

In order to prevent the transmission of vibration between power supplies and gyros from interfering with bearing noise measurements, it was necessary to mount all the equipment on rubber shock mounts. The noise level determinations were made with a General Radio type 759B sound-level meter equipped with a vibration pickup and control box. The inertia operated, piezoelectric pickup responded to acceleration while the control box provided integrating circuits. The pickup was designed to operate below the resonant point, which in this instrument occurred at approximately 1500 cycles per second (12). The sound-level meter read in decibels within the audio-frequency range, although readings may be converted to vibration displacement, velocity, or acceleration. The noise levels of most of the bearings studied were in the neighborhood of 70 to 80 decibels, corresponding to accelerations of 27 to 86 inches per second per second, respectively. The total noise measured by the sound-level meter consisted of the bearing noise spectrum superposed on that of the vibration of structural parts of the gyro.

Analyses of the noise components were made by using the sound-level meter in conjunction with a Panoramic Sonic analyzer. While this instrument was originally designed for use in studying phenomena in electrical circuits, it was used in this investigation for noise analysis. The instrument separated the frequency components of a complex wave and simultaneously measured their amplitude on a cathode-ray screen. The screen was calibrated horizontally in frequency and vertically in voltage. The frequency scale was approximately logarithmic from 40 to 20,000 cycles per second, while the voltage scale

was calibrated over a 40 decibel range. The noise analyses patterns and the calibrated scale on the face of the cathode-ray tube were photographed simultaneously with a modified Dumont 271-A oscilloscope camera using Ansco Supreme film. To accomplish this satisfactorily, a device was developed whereby a series of low-voltage incandescent lamps were placed in a circle around the large end of the cathode-ray tube slightly behind the face of the tube. The tube screen, but not the scale, was thus illuminated through the edge of the tube face and from the rear through the transparent section of the tube wall adjacent to the face. By adjusting the degree of illumination, the scale was made to stand out against the lighted screen without interfering with photographing satisfactorily the electron beam pattern. In making a recording, the camera was opened only for the duration of the one-second sweep of the electron beam.

Because of the random movement of many of the noise peaks observed in the bearing noise spectra, it was considered advisable to make at least three photographs of each spectrum. Average values of each frequency component were then used to study changes in noise intensity at any given frequency during the time the bearing was under test. Due to the complexity of the noise spectra, this was a very tedious method, but it appeared to be the only way of obtaining sufficient information relative to over-all change in noise intensity at any given frequency.

Near the end of the tests, a miniature barium titanate accelerometer was used as a transducer in conjunction with the Panoramic Sonic analyzer. This vibration pickup, supplied by the National Bureau of Standards, had an essentially flat response from a few cycles to the region of 10,000 cycles per second. The resonant frequency was considerably above the range of the Panoramic Sonic analyzer. Sensitivity was in the order of 2 millivolts per "g" and the pickup had a dynamic range of from 0.5 "g" to at least 10,000 "g" (13). Since data in terms of decibels, absolute sound pressure, had been obtained with the General Radio vibration pickup, the barium titanate accelerometer calibration was converted to the same units at 1000 cps. In a comparison of a number of noise spectra of the same bearings using both transducers, the agreement was only fair. This may be partially attributed to differences in the characteristics of the frequency-response curves of the two devices or to the fact that different methods of calibration were used.

When using the General Radio vibration pickup, the rather inaccessible positions of some of the gyro bearings made it necessary to approach them from more than one position. On the Gun Sight Mark 20 gyros, the pickup prod was placed on the end-bell housings of the gyro motor at right angles to the rotor shaft. Data were obtained on the air-driven gyros by placing the prod of the pickup directly on the rotor bearing locking sleeves and parallel to the rotor axes. Measurements on the upper bearing of the Stable Element gyro were made in the same manner as those on the air-driven gyros, while those on the lower bearing were obtained by placing the pickup prod on the lower bearing cap at right angles to the rotor axis. The noise levels of the Gunar gyros were obtained by placing the prod of the pickup on the cases at right angles to the rotor axes. Thus, the over-all noise level of the gyro was obtained rather than that of either bearing alone. Data taken with the barium titanate accelerometer on the large gyros were obtained by screwing the pickup directly on the bearing locking sleeves or bearing caps such that the forces being measured were those parallel to the rotor axes. When the accelerometer was used on the C-31 gyro, the rubber shock mount used to suspend the gyro was removed and replaced by the accelerometer. The gyro was placed on sponge rubber and the forces measured were those at right angles to the rotor axis.

Gun Sight Mark 20 Gyros

Tests of the two Gun Sight Mark 20 gyros "C" and "D" had been in progress for 7000 and 5000 hours, respectively, at the time the earlier work was reported (7, 8). These tests were continued to 10,000 hours. Data covering the operation of these gyros are

given in Table 1. Rotor speeds and power input remained essentially unchanged throughout the tests. Changes in bearing temperatures were nominal and reflected for the most

TABLE 1
Operating Data on the Electric
Gyros "C" and "D" With Synthetic Lubricants

| Gyro | Lubricant | Operation (hr) | Coast Time (sec) | Bearing temperatures (°F) | | Bearing Noise Level (db) | |
|------|------------------------------------|-------------------|---------------------|------------------------------|----------|-----------------------------|----------|
| | | | | Hub-End | Cage-End | Hub-End | Cage-End |
| "C" | Spec. 14-0-20 oil | 0 | 288 | 96 | 99 | 82 | 80 |
| | | 2000 | 327 | 99 | 101 | 81 | 80 |
| | | 4000 | 330 | 95 | 97 | 82 | 81 |
| | | 6000 | 324 | 95 | 96 | 83 | 82 |
| | | 8000 | 320 | 94 | 94 | 83 | 81 |
| | | 10,000 | 318 | 97 | 96 | 82 | 80 |
| "D" | Spec. MIL-G- 15793 grease | 0 | 192 | 104 | 105 | 80 | 76 |
| | | 2000 | 238 | 102 | 101 | 82 | 78 |
| | | 4000 | 244 | 92 | 93 | 82 | 78 |
| | | 6000 | 246 | 90 | 90 | 82 | 78 |
| | | 8000 | 248 | 93 | 94 | 81 | 78 |
| | | 10,000 | 250 | 99 | 98 | 81 | 78 |

part the variation in ambient temperature. Coast times for both gyros showed a steady increase for the first 2500 hours. For the remainder of the tests, the "C" gyro exhibited only small fluctuations in coast time while that of the "D" gyro continued to rise slowly. Since the rotors operated at constant speed, the initial effect of windage on coast time would be reproducible. This would indicate that the bearing friction of the gyros decreased during the early stages of the tests possibly due to a "wearing in" of the bearings during this period. The absence of any appreciable increase in rotor bearing noise level during the tests is further evidence that very little detrimental bearing wear occurred. Data given in Table 1 shows a rather significant difference between hub-end and cage-end bearing noise. This was observed in the same type gyros studied earlier (7, 8) and may be due to the presence of the rather heavy eddy-current disc at the hub-end of the gyro.

Analyses of the bearing noise components using the Panoramic Sonic analyzer and the General Radio pickup revealed that the noise spectra of the bearings of both the "C" and "D" gyros were similar. Noise frequencies were found over the range of 180 cps to about 2000 cps. The principal frequencies usually appeared in the neighborhood of 240, 480, 750, 900, 950 to 980, and 1200 through 1800 cps. The noise spectrum of the "C" gyro cage-end bearing after 10,000 hours of operation (Fig. 1) is rather unique in that while it is very similar to those of the other gyro bearings, the frequency in the neighborhood of 240 cps is not prominent. Spectra of the Gun Sight Mark 20 gyro bearings observed during the operation of the gyros have shown no significant change in characteristics after 10,000 hours of operation. Observations made on other gyros indicate that the principal well defined peaks, were, for the most part, vibrations of structural parts of the gyro. The peak at about 240 cps was probably due to the rotor speed or power frequency of 235 cps. Some of the other peaks may also have been due to electrical phenomena within the gyro motor. This condition has been observed by another laboratory (14) investigating ball bearing noise and vibration in electric motors. The frequency at 1500 cps may have been a function of the resonant frequency of the vibration pickup which was also at about 1500 cps.

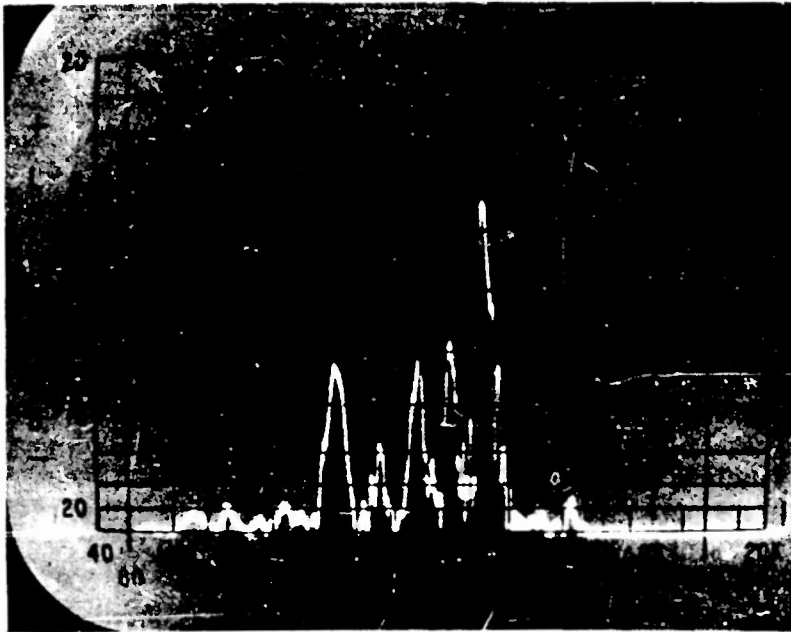


Figure 1 - Sound spectrum of Gun Sight Mark 20 "C" gyro cage-end rotor bearing. Hours of Operation: 10,000; Lubricant: Specification (ORD) 14-0-20 oil; Zero \pm 70 decibels; Over-all noise level: 78 decibels. Vibration pickup used as transducer.

At operating speeds of about 14,100 rpm, eccentricity of the rotor bearing inner race would give rise to a frequency of 235 cps. The cage assemblies of the bearings used in the Gun Sight Mark 20 gyros revolved at about 85 rps (slippage neglected). When the number of balls in each bearing is taken into account, a fundamental frequency of about 683 cps would be generated by the bearing if a single ball dent existed on the outer raceway. When the relative rotational speeds of the cage and inner race are considered, a similar defect on the inner raceway could give rise to a frequency of about 1200 cps. In view of other possible combinations of raceway and ball defects which may exist in ball bearings, it is thus seen that these rotor bearings could be responsible for some of the noise frequencies observed as well as exciting certain parts of the gyro to resonance. However, many of the frequencies observed show no easily discernible relation to bearing design.

After the completion of the tests, the Gun Sight Mark 20 gyros were stored without further lubrication. After a period of approximately one year the "C" gyro was disassembled and the bearings examined. Both bearings were well supplied with oil and examination of the races revealed typical ball tracks characterized by one or two bright lines with lightly abraided areas lying on either side. The balls were in good condition although the several tracks indicated that the axes of rotation had shifted a number of times. The "D" gyro was disassembled after being stored for about two years. While the bearings were still adequately lubricated, examination of the grease revealed it to be extremely soft and in a semifluid condition, probably a result of the high speed at which the gyro operated. Inspection of the bearings indicated some wear had taken place. A roughened zone in the ball track resembling light corrosion was observed on the outer race of the cage-end bearing. The balls showed some indication of wear, one being characterized by a groove apparently caused by an abrasive particle imbedded in the phenolic retainer. The races of the hub-end bearing were in good condition, although a slight brownish color was discernible in the abraided portion of the wear tracks.

Stable Element Mark 6 Gyro

The heavy Stable Element Mark 6 gyro was first set up for operation on Specification (ORD) 14-0-20 diester oil. After approximately 85 hours of operation the noise level of the lower bearing rose in cycles as much as 10 decibels above normal and the change in noise level was quite audible. Bearing temperature flashes of approximately 60°F occurred every 30 minutes. Upon examination after disassembly of the gyro, the lower bearing appeared dry and the balls had assumed the brown coating typical of instrument bearings about to fail because of lack of lubricant or overheating. The bearing exhibited considerable roughness when rotated by hand. The upper bearing, which was lubricated by a wick feed system, was well supplied with oil. The lower bearing of this gyro was lubricated by means of a tapered spindle attached to the rotor, the lower tip of which was immersed in oil in a sump in the lower bearing cap. The oil traveled up the spindle and out onto the bearing by a combination of cohesive and centrifugal forces. It was found that the Specification (ORD) 14-0-20 oil would not travel up the spindle in sufficient quantity to adequately lubricate the bearing. However, by raising the level of the oil in the sump about 1/8 inch, this difficulty was overcome. This was accomplished by filling the oil well or sump with the gyro level instead of in the tilted position described in BuOrd Publication OP 1063.

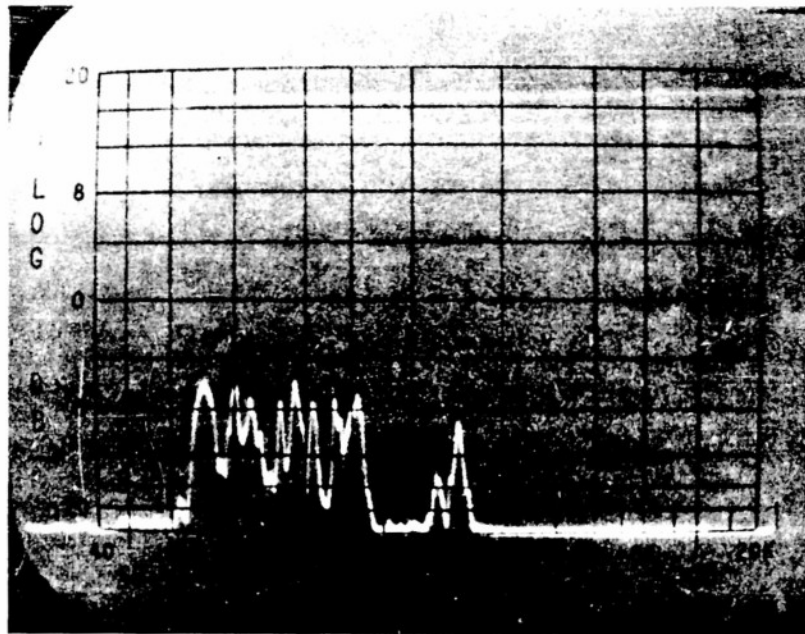


Figure 2 - Sound spectrum of Stable Element Mark 6 gyro lower bearing. Hours of Operation: 3; Lubricant: Specification(ORD) 14-0-20 oil; Zero \equiv 70 decibels; Over-all noise level: 70 decibels. Vibration pickup used as transducer.

Noise analyses spectra were photographed at the beginning of the test (Fig. 2) and again after the lower bearing became noisy (Fig. 3). The spectra are presented here to show the reaction of the noise analysis apparatus to an over-all increase in bearing noise of about 5 to 7 db at the instant the photograph was made. Note that all the peaks appearing at the beginning of the test also appeared after the bearing began to fail. With the exception of those in the 150-cps to 200-cps region, the heights of all peaks had increased. In addition, particularly in the region of 400 cps, several additional frequencies appeared which were not evident in Fig. 2 or were of an extremely low order of magnitude.

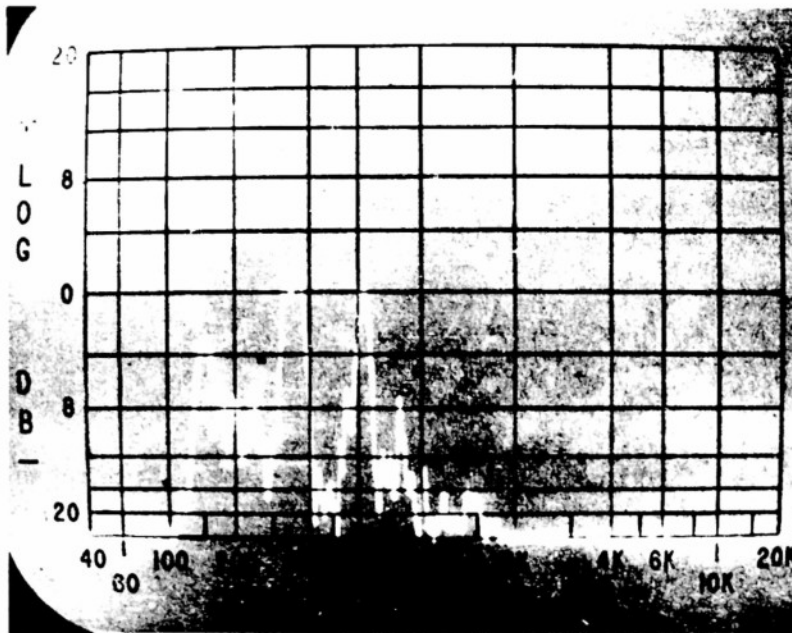


Figure 3 - Sound spectrum of Stable Element Mark 6 gyro lower bearing. Hours of Operation: 85; Lubricant: Specification (ORD) 14-0-20 oil; Zero \pm 70 decibels; Over-all noise level: 76 decibels. Vibration pickup used as transducer.

TABLE 2
Operating Data on the Mark 6
Stable Element Gyro With Specification (ORD) 14-0-20 Oil

| Operation (hr) | Deceleration (sec) | 900-rpm Coast Time (sec) | Bearing Temperature (°F) | | Bearing Noise Level (db) | |
|-------------------|-----------------------|--------------------------------|-----------------------------|------------------|-----------------------------|------------------|
| | | | Upper Bearing | Lower Bearing | Upper Bearing | Lower Bearing |
| 0 | 124 | — | 131 | 142 | 72 | 78 |
| 500 | 124 | — | 131 | 144 | 73 | 78 |
| 1000 | 124 | 1300 | 131 | 145 | 73 | 78 |
| 1500 | 125 | 1280 | 132 | 146 | 73 | 79 |
| 2000 | 125 | 1290 | 132 | 146 | 73 | 79 |
| 2500 | 125 | 1370 | 133 | 147 | 73 | 79 |
| 3000 | 126 | 1480 | 133 | 147 | 72 | 79 |

New rotor bearings were fitted to the Stable Element Mark 6 gyro and the instrument operated for 3000 hours on Specification (ORD) 14-0-20 oil using the modified oiling technique described earlier. Operation was satisfactory with no significant changes taking place. Rotor speed and power input remained essentially unchanged. Data given in Table 2 show that deceleration and 900 rpm coast times increased slightly. Bearing temperatures reflected changes in ambient temperatures. The temperature of the lower bearing ran 12°F to 14°F above that of the upper bearing partially because of the location of the gyro motor windings with respect to the lower bearing. Rotor bearing noise levels remained essentially unchanged throughout the test.

Noise analyses of the upper bearing showed the more prominent peaks to be at approximately 150, 200 to 250, 290, 350, 400, 550, 650, and 900 cps, and several over the range of 1000 to 1500 cps. Analyses of the lower bearing noise revealed a similar frequency distribution, but it was noted that in the 400- to 1000-cps region, there were more high energy peaks than were seen in the upper bearing spectra. This may have been due to the fact that while the upper bearing was mounted very close to the mass of the rotor, the lower bearing was mounted on a comparatively flexible extended rotor shaft. Analyses made at intervals during the test indicated gradual changes in noise intensity at certain frequencies. Increases in intensity of a few decibels in the upper bearing were noted at 900, 1100, 1300, and 1500 cps; while lower bearing frequencies of 400, 650, 1100, and 1500 cps also increased slightly. On the other hand, upper bearing noise at 350, 400, 550, and 650 cps decreased slightly and the same was observed at 150, 250, and 900 cps in the lower bearing.

Examination of the bearings after the test of the Stable Element gyro indicated that both bearings were well lubricated. Ball tracks on the races were quite normal, although the lower bearing ball track on the inner race had apparently shifted slightly during operation. The balls showed some wear but there were no signs of imminent failure. A number of balls had small circular markings on them, undoubtedly caused by wear against the retainer.

New bearings were installed on the gyro and lubricated with MIL-G-15793 grease as described earlier. They were not relubricated during the 5000 hours of operation of the gyro. Power input and rotor speed varied only slightly during this time. As shown in Table 3, deceleration and 900-rpm coast times showed a small but rather regular decrease from about 1000 hours of operation until the conclusion of the test. Data taken during the first 1000 hours of operation indicated a gradual increase of values as the grease became distributed and the bearings "wore in." As before, fluctuations in bearing temperatures reflected changes in ambient temperatures. Bearing noise levels increased about 3 decibels during the test; this increase was somewhat more than that obtained with diester oil lubricants for the same number of hours of operation.

TABLE 3
Operating Data on the Mark 6
Stable Element Gyro With Specification MIL-G-15793 Grease

| Operation (hr) | Deceleration (sec) | 900-rpm Coast Time (sec) | Bearing Temperature (°F) | | Bearing Noise Level (db) | |
|-------------------|-----------------------|--------------------------------|-----------------------------|------------------|-----------------------------|------------------|
| | | | Upper Bearing | Lower Bearing | Upper Bearing | Lower Bearing |
| 0 | 131 | 1350* | 136 | 142 | 71 | 76 |
| 1000 | 136 | 1680 | 133 | 145 | 72 | 78 |
| 2000 | 136 | 1660 | 135 | 147 | 73 | 78 |
| 3000 | 135 | 1640 | 135 | 148 | 73 | 78 |
| 4000 | 134 | 1620 | 134 | 146 | 73 | 79 |
| 5000 | 132 | 1600 | 132 | 143 | 74 | 79 |

*After 20 hours of operation

Analyses of the bearing noise with the Panoramic Sonic analyzer resulted in spectra very similar to those obtained on the previous run. An analysis of the upper bearing noise at the start of the test is shown in Fig. 4. The principal peaks may be observed near that of the power frequency, and also at 250, 700, 900, 1100, and 1300 cps with many

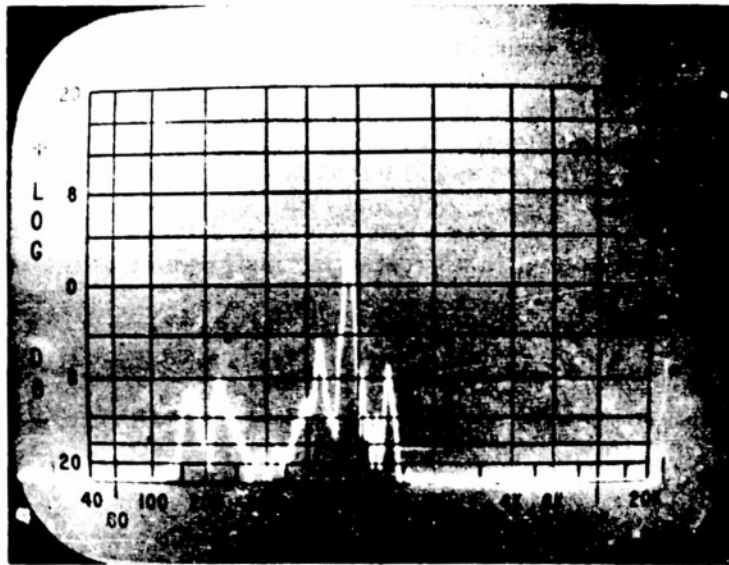


Figure 4 - Sound spectrum of Stable Element Mark 6 gyro upper bearing. Hours of Operation: 2; Lubricant: MIL-G-15793 grease; Zero \pm 70 decibels; Over-all noise level: 72 decibels. Vibration pickup used as transducer.

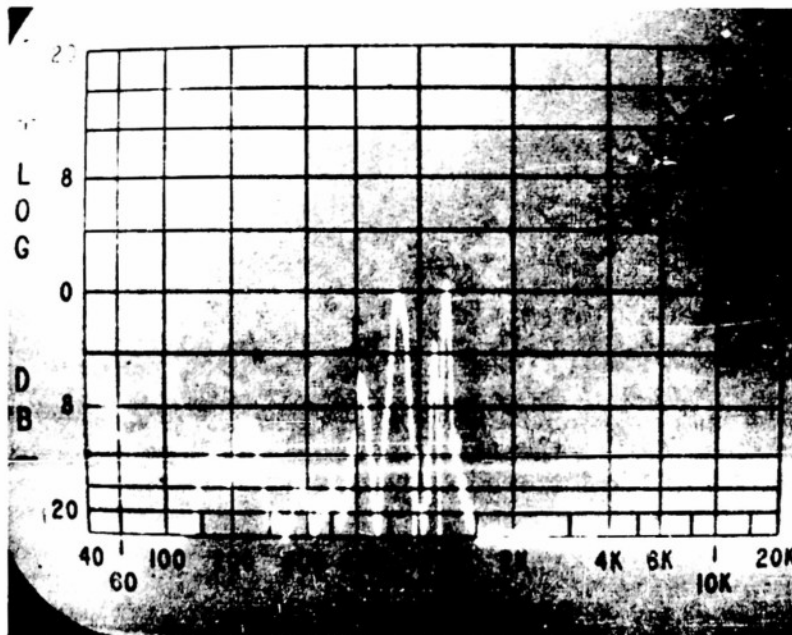


Figure 5 - Sound spectrum of Stable Element Mark 6 gyro upper bearing. Hours of Operation: 5000; Lubricant: MIL-G-15793 grease. Zero \pm 70 decibels. Vibration pickup used as transducer.

others of lower magnitude. Analyses of all the noise spectra photographed during the test indicated that frequencies of about 1100 and 1300 cycles were probably responsible for a substantial portion of the rise in over-all noise level. This may be seen in the noise spectrum of the upper bearing at the end of the test (Fig. 5). Only small changes occurred at the other frequencies. A similar rise in the noise level of the lower bearing was observed to be due to increases in sound intensity at approximately the frequency of the power supply and at 250, 400, 450, 900, and 1000 cps. Noise at only a few frequencies decreased in intensity during the test. Analyses made during the oil-lubricated and grease-lubricated runs revealed that in a great many instances, the greatest change in the sound intensity at any one frequency occurred during the first 1000 hours of operation of the gyro. These initial changes in noise intensity did not always go in the same direction as the over-all change in the value in the frequency involved. With the exception of the lower bearing in the grease-lubricated gyro, frequency peaks which predominated decreased in intensity during the first 1000 hours of operation. This may be considered another demonstration of the "wearing in" phenomenon mentioned earlier. On the contrary, all the frequencies observed in the lower bearing spectra increased during the first 1000 hours of operation. This may be an indication that this bearing was somewhat inferior to the other bearings even when new. It was evident that little "wearing in" or smoothing effect occurred. However, after the first 1000 hours of operation, further deterioration seemed to be no greater than that of the upper bearing.

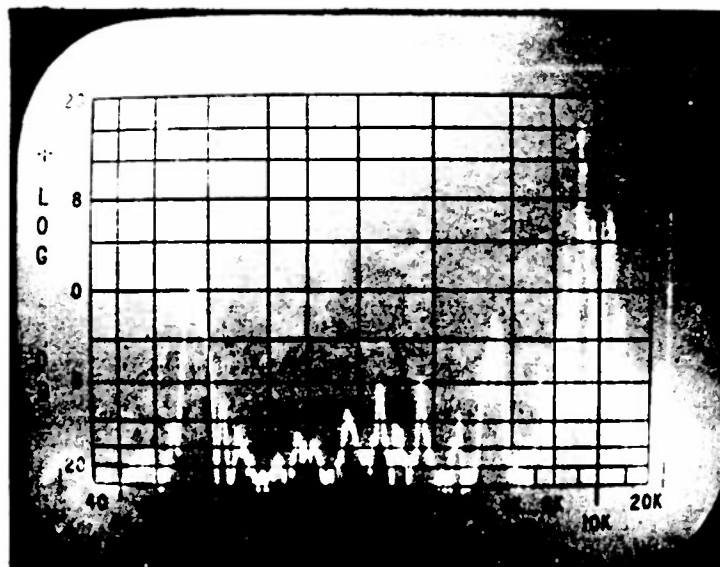


Figure 6 - Sound spectrum of Stable Element Mark 6 gyro upper bearing. Hours of Operation: 5000; Lubricant: MIL-G-15793 grease; Zero \equiv 72 decibels (at 1000 cps). Barium titanate accelerometer used as transducer.

Since the General Radio vibration pickup did not respond well to frequencies above 2000 cps (12), noise spectra of the Stable Element bearings were studied with the Panoramic Sonic analyzer using the barium titanate accelerometer as a transducer. The spectrum of the upper bearing at the end of the test is shown in Fig. 6. It is seen that over the range covered by the General Radio vibration pickup approximately the same frequencies appeared. The intensities (in terms of decibels, absolute sound pressure) of the corresponding frequencies did not necessarily agree. This was due either to inherent differences in the characteristics of the response curves of the two transducers or to

the fact that they were calibrated by different methods, as mentioned earlier. When the accelerometer was used as a transducer, the Panoramic Sonic analyzer was operated at full gain. This resulted in a certain amount of electrical interference in the region of 100 cps or below, and hence tended to mask any noise recorded in this region. Therefore, the signals observed should be considered in this light and for the purposes of this report have been disregarded. It was also found that when using the analyzer at full gain, or with an auxiliary amplifier, the transducer cable tended to act as a pickup, particularly near the power frequency. This is shown in Fig. 6 where the frequency near 150 cps has been accentuated because of these "cable effects." After this phenomenon was encountered, the effect was minimized by taking pains to see that the cable did not come into mechanical contact with the gyro. However, many peaks appeared above 2000 cps with those of the greatest number and intensity appearing in the neighborhood of 8000 cps. It is also of interest to note that the intensity of the noise in the high-frequency region was much higher than the noise in the frequency band recognized by the General Radio apparatus. Thus, the high-frequency noise represents a large portion of the overall noise of the gyro as detected by ear. Examination of the lower bearing spectrum with the accelerometer after 5000 hours of operation (Fig. 7) revealed a very similar situation. However, the higher level peaks were grouped in the region of 6000 cps.

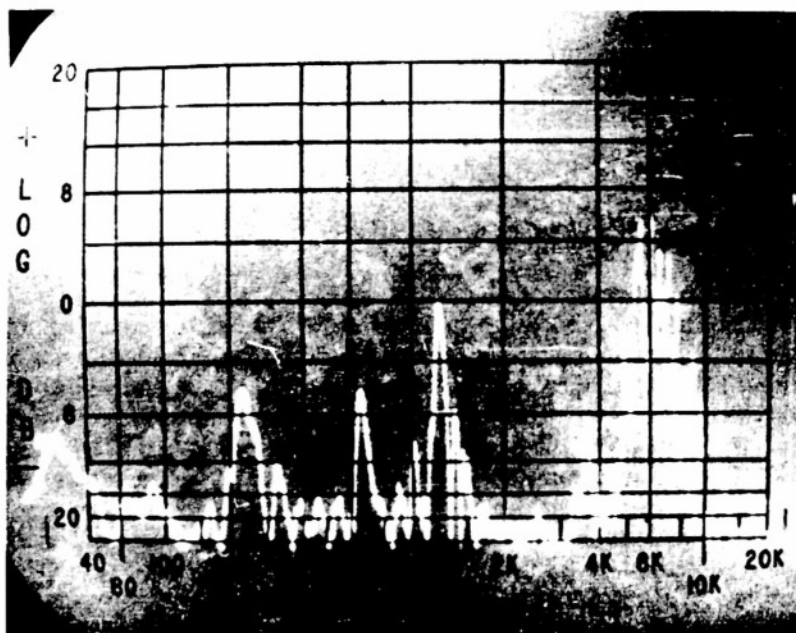


Figure 7 - Sound spectrum of Stable Element Mark 6 gyro lower bearing. Hours of Operation: 5000; Lubricant: MIL-G-15793 grease; Zero \pm 72 decibels (at 1000 cps). Barium titanate accelerometer used as transducer.

It had been suggested in the earlier report (7, 8) that many of the noise peaks observed in analyses of the Stable Element Mark 6 gyro bearings were due to resonant vibrations of structural parts of the gyro. In order to determine some of the natural frequencies present, a series of noise analyses were made and photographed with the gyro rotor at rest while the instrument was excited by striking the case a sharp blow with a hammer. Only one blow was struck during a single sweep of the analyzer electron beam and one picture was made during a given sweep. The time of impact was varied over the one-second period in each case in order to cover adequately the entire

frequency range. The initial shock peak was ignored. When the vibration pickup was used on the upper bearing, 13 different frequencies ranging from 95 cps to 2200 cps were observed in a total of 9 analyses. The lower bearing pattern revealed 23 frequencies in a total of 23 pictures ranging from about 90 cps to 2000 cps. A few analyses made with the accelerometer revealed 19 different frequencies from 130 to 13,000 cps. Included were a number in the region of 6000 and 8000 cps. Most of the frequencies observed below 2000 cps were those observed earlier with the vibration pickup. Analysis of data in the region above 2000 cps was difficult because of the fast writing speed of the electron beam at the higher frequencies.

Possible sources of excitation to resonance of the structural parts of the gyro were considered. Noise peaks at about 1500 cps observed when using the vibration pickup may have been amplified by the fact that the resonant frequency of the pickup was near this value. However, noise peaks near 1500 cps were also seen in the spectra while using the accelerometer. As mentioned earlier, it has been suggested by another laboratory (14) that some peaks may be due to or excited by electrical phenomena within the gyro motor. Analyses made with the power turned on and the gyro rotor locked revealed noise peaks at about 230, 290, 550, 850, and 1100 cps. Of these, the 290-cps peak was of the greatest intensity. This value was approximately twice that of the power frequency of 146 cps. During these tests, no appreciable drop in power supply frequency was observed in the one second required to make a photograph of the noise spectrum. The electrical stresses resulting from the locked rotor were more severe than those encountered under normal operating conditions and the data are reported here to show what frequencies from this source might be encountered in the gyro under starting conditions or under heavy load. That the effect of the power frequency appeared to be minor under normal operation conditions was proven by making a number of noise analysis pictures with the power to the gyro cut off while each picture was made. A study of these analyses revealed no appreciable change in the spectra as a result of turning off the power, regardless of which transducer was used.

Study of the rotational speed of the rotor and bearing components showed that since the rotor revolved about 146 rps, any eccentricity of the rotor bearing inner race would produce a fundamental frequency of that value. At normal rotor speeds, the bearing cage assembly revolved at about 43 rps. When the 5 balls of each bearing were considered, a single ball dent of the outer race could give rise to a fundamental frequency of about 215 cps. The speed of the inner race with respect to that of the bearing retainer is about 103 rps. Taking into consideration the number of balls in the bearing, a fundamental frequency of 515 cps might be expected for a single defect on the inner race. Defects in the balls themselves would add to the number of frequencies involved. It is thus seen that a combination of bearing raceway defects could give rise to many frequencies in the noise spectra as well as being available to excite many structural parts of the gyro to resonance.

After operation of the Stable Element gyro with grease, examination of the bearings showed that the lubricant was much like the original. A light brown deposit was observed on the ball tracks which could easily be wiped off. While the balls indicated some wear, the most outstanding characteristics observed were the appearance of several small circular wear grooves caused by the rubbing of the balls on the phenolic retainers. Some of these grooves indicated more wear than the wear tracks on the balls. There appeared to be a small amount of corrosion in the wear track on the lower bearing outer race although none was observed on the inner race. This condition may have been responsible for a slight rough "feel" of the bearing observed at the time of disassembly of the gyro. However, there was no indication that the bearings would not have operated for a longer period.

Gun Sight Mark 15 Gyros

The train and elevation gyros from three Gun Sights Mark 15 designated as sets "C," "D," and "E," respectively, were operated for 5000 hours. Air pressure at the gyro nozzles was maintained at 7 inches of mercury.

TABLE 4
Operating Data on the Gun Sight Mark 15
Gyros With Specification (ORD) 14-0-20 Oil

| Gyro | Operation (hr) | Rotor Speed (rpm) | Deceleration (sec) | 900-rpm Coast Time (sec) | Bearing Temperatures (°F) | | Bearing Noise Level (db) | |
|-----------|----------------|-------------------|--------------------|--------------------------|---------------------------|-----|--------------------------|-----|
| | | | | | A* | B** | A* | B** |
| TRAIN | 0 | 9000 | 27.6 | — | 140 | 140 | 73 | 73 |
| | 1000 | 9000 | 28.1 | 1280 | 140 | 140 | 71 | 71 |
| | 2000 | 8900 | 29.8 | 1860 | 140 | 140 | 70 | 71 |
| | 3000 | 8880 | 30.8 | 2000 | 140 | 140 | 70 | 72 |
| | 4000 | 8850 | 31.0 | 1960 | 140 | 140 | 71 | 71 |
| | 5000 | 8760 | 31.0 | 1500 | 140 | 140 | 73 | 69 |
| ELEVATION | 0 | 9000 | 27.2 | — | 139 | 140 | 68 | 68 |
| | 1000 | 8950 | 27.4 | 1390 | 138 | 139 | 69 | 70 |
| | 2000 | 8960 | 28.5 | 1430 | 138 | 138 | 69 | 70 |
| | 3000 | 8960 | 29.0 | 1640 | 138 | 138 | 70 | 70 |
| | 4000 | 8960 | 29.2 | 1570 | 139 | 139 | 69 | 69 |
| | 5000 | 8920 | 29.2 | 1420 | 140 | 139 | 68 | 69 |

* Data for train gyro rotor bearing No. 1 and elevation gyro rotor upper bearing.

** Data for train gyro rotor bearing No. 2 and elevation gyro rotor lower bearing.

Data obtained on the "C" gyros are given in Table 4. Rotor speeds of the train and elevation gyros had dropped approximately 2.7 percent and 0.8 percent, respectively, by the time the test had ended. This was an over-all improvement in operation over that of the previous Gun Sight Mark 15 gyros studied (7, 8). Here the rotor speeds of the two train gyros dropped 4.4 percent and 2.6 percent each and those of the elevation gyro rotors 1.5 percent and 1.1 percent, respectively, after 5000 hours of operation. Deceleration times of the "C" gyros for the first 1000 rpm gradually increased during the test, probably due to reduced windage loss at the lower rotor speeds observed near the end of the test. The time required for the train gyro to stop from a speed of 900 rpm increased to a maximum from 2500 to 4000 hours and decreased to the end of the test. The 900 rpm coast time of the elevation gyro rotor behaved somewhat similarly, increasing to a maximum at about 3000 hours. This would indicate that the bearing friction gradually decreased as the bearing became "smoother" with use until initial deterioration began to set in during the latter part of the test. Bearing temperatures changed little throughout the entire test. Over-all bearing noise levels of train gyro bearing No. 1 remained essentially unchanged at the end of the test although it had decreased somewhat earlier. Noise of bearing No. 2 behaved somewhat similarly except some reduction of intensity was noted near the end of the run. On the contrary, noise levels of the elevation gyro bearings increased slightly during the run but began to decrease by the end of the period of operation.

Analyses of the rotor bearings with the General Radio pickup all gave rather similar patterns. Typical of the analyses of these bearings are those of the train gyro bearing No. 2 and the elevation gyro upper bearing shown in Figs. 8 and 9, respectively. The train gyro bearing noise peaks appearing most prominently and consistently throughout the run were observed at about 350, 400, 450, 620 to 650, 800, 1200, and 1300 cps.

Analyses of the elevation gyro bearings differed in characteristics from those of the train gyro bearings principally in the region of about 250 cps and 1000 to 2000 cps. Here considerably more activity was observed. As the test progressed, the intensity of several noise frequencies varied in a random manner but certain trends were rather pronounced. Noise of the train gyro bearings increased in intensity 3 db or more at 620, 650, 750, 900, and 1200 cps. Decreases were noted at 350, 400, 450, 570, 800, 1200, and 1300 cycles per second. On the other hand, the elevation gyro bearings showed a tendency to increase in noise at 300, 550, 1100, and 1200 cps. The opposite effect was noted at about 300, 350, 400, 450, 650, 800, 900, and 1600 cps.

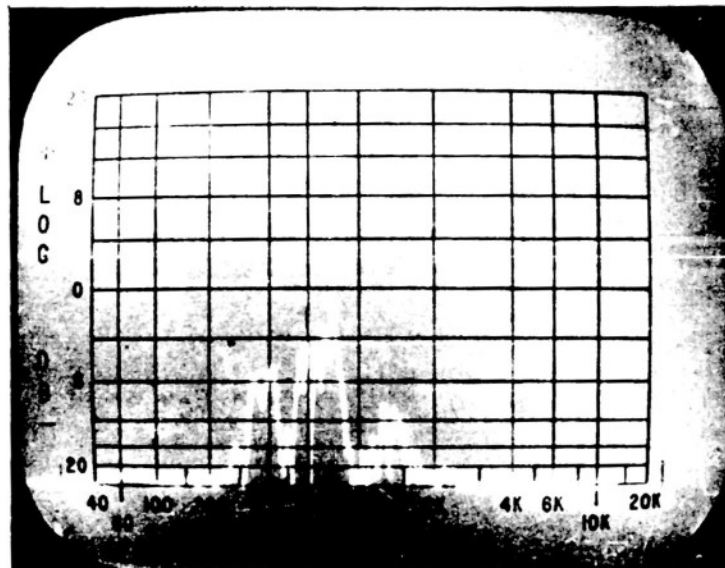


Figure 8 - Sound spectrum of Gun Sight Mark 15 "C" train gyro bearing No. 2. Hours of Operation: 3; Lubricant: Specification (ORD) 14-G-20 oil; Zero \pm 70 decibels; Over-all noise level: 73 decibels. Vibration pickup used as transducer.

After being allowed to stand with the case closed for about one year, the Gun Sight Mark 15 "C" gyros were disassembled and the bearings examined. The train gyro bearings were still covered with an adequate film of oil and the oil pads were still wet with the lubricant. However, the elevation gyro bearings had a very thin film of oil on them and the felt oil pads were quite dry. All the bearings were corroded very lightly in the ball tracks but there was evidence that this had taken place after the completion of the test. The wear tracks on the train gyro bearings were hardly visible indicating very little wear. The elevation gyro bearings were similar in appearance to those of the train gyro with the exception that very light corrosion was observed on the balls. These small bearings all were characterized by considerable clearance between the balls and races, and consequently the wear tracks all appeared quite near the shoulders of the raceway grooves. In general, there was nothing found that would indicate imminent failure of these bearings.

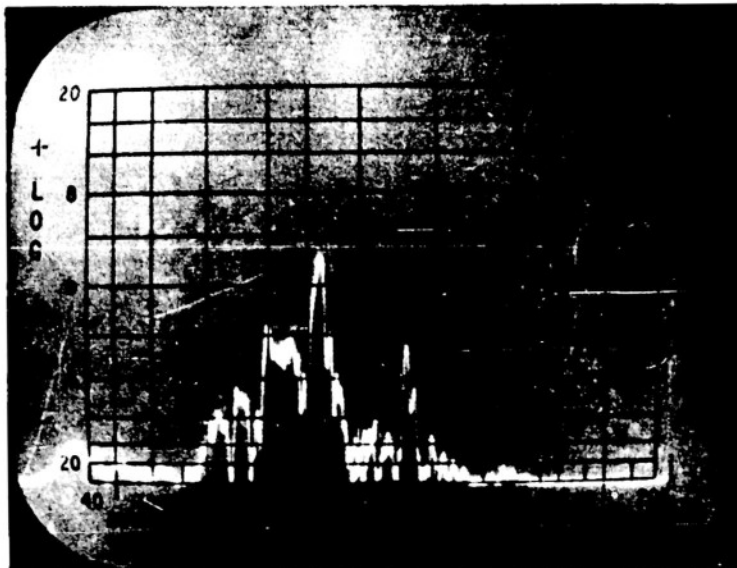


Figure 9 - Sound spectrum of Gun Sight Mark 15 "C" elevation gyro upper bearing. Hours of Operation: 3; Lubricant: Specification (ORD) 14-0-20 oil; Zero = 60 decibels; Over-all noise level: 68 decibels. Vibration pickup used as transducer.

The operating data obtained on the "D" gyros lubricated with MIL-G-15793 grease are given in Table 5. A somewhat greater reduction in rotor speeds was observed than was found in the gyros lubricated with diester oil. Speed losses of the train and elevation gyros were 3.3 percent and 2.2 percent, respectively. Reduction of speed of the train gyro rotor fell between those attained for the same number of hours of operation of the two Gun Sight Mark 15 gyros operated on petroleum oil (7, 8), while the speed of the elevation gyro rotor dropped below those of the elevation gyros studied earlier. Again time for decelerating the first 1000 rpm below operating speed gradually increased because of a lowering of the rotor speed near the end of the test. The train gyro 900-rpm coast test, although rather erratic, increased gradually. However, that of the elevation gyro at the end of the test was about the same as at the start, although a reduction in coast time was noted during the course of the test. Bearing temperatures changed only slightly during the 5000 hours of operation. The noise level of train gyro bearing No. 1 increased about 2 db while that of the opposite bearing changed very little. Noise of the elevation gyro bearings were characterized by a reduction in intensity during the middle of the run while at the end the intensity was slightly less than at the start.

The noise analyses spectra of the train gyro bearings were quite similar in appearance to those obtained on the "C" gyros. Major peaks observed in both bearings included those at about 330, 500, 650, 700, 800, and a scattering of peaks of lesser prominence over the range 1000 to 1500 cps. However, the spectra of the elevation gyro bearings were quite different. Almost all the noise was emitted in the region 600 to 800 cps with the major peak at about 700 cps. Typical of all the spectra photographed of both elevation gyro bearings during the test was that of the lower bearing after 5000 hours of operation (Fig. 10). In the analysis of the train gyro bearing noise spectra pictures made during the tests, certain trends were noted. Noise components which increased 3 db or more included those at 420, 500, 550, 750, 900, 950, 1200, and 1500 cps. However, decreases of like amount or more were found only at 220, 380, and 1700 cps. The much simplified spectra of the elevation gyro bearings were characterized by noise increase only at about 180, 500, 900, and 1400 cps. Components which decreased 3 db or more

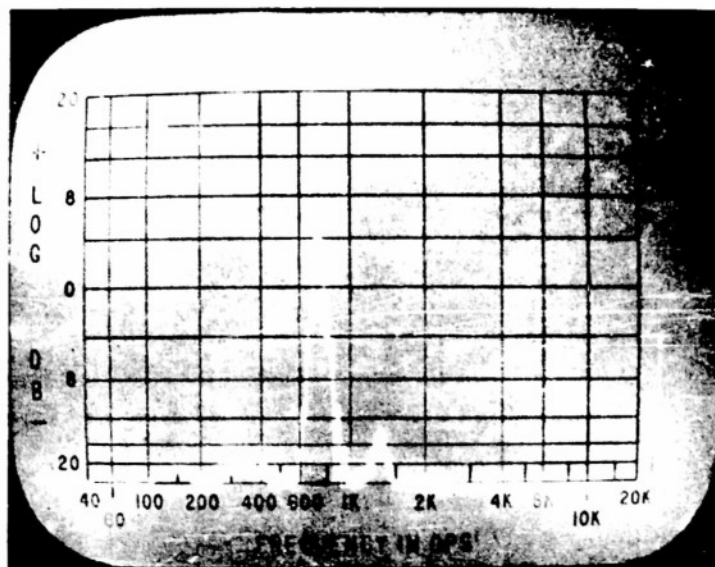


Figure 10 - Sound spectrum of Gun Sight Mark 15 "D" elevation gyro lower bearing. Hours of Operation: 5000; Lubricant: MIL-G-15793 grease; Zero \pm 70 decibels; Over-all noise level: 75 decibels. Vibration pickup used as transducer.

TABLE 5
Operating Data on the Gun Sight
Mark 15 Gyros With MIL-G-15793 Grease

| Gyro | Operation (hr) | Rotor Speed (rpm) | Deceleration (sec) | 900-rpm Coast Time (sec) | Bearing Temperatures ($^{\circ}$ F) | | Bearing Noise Level (db) | |
|-----------|----------------|-------------------|--------------------|--------------------------|--------------------------------------|-----|--------------------------|-----|
| | | | | | A* | B** | A* | B** |
| TRAIN | 0 | 9000 | 27.4 | - | 140 | 140 | 73 | 75 |
| | 1000 | 8950 | 28.2 | 1470 | 140 | 141 | 74 | 76 |
| | 2000 | 8900 | 29.0 | 1660 | 139 | 139 | 74 | 76 |
| | 3000 | 8900 | 29.6 | 1860 | 140 | 140 | 75 | 75 |
| | 4000 | 8840 | 30.4 | 1980 | 140 | 139 | 76 | 75 |
| | 5000 | 8700 | 31.6 | 1960 | 135 | 134 | 75 | 75 |
| ELEVATION | 0 | 9000 | 28.8 | - | 141 | 141 | 74 | 73 |
| | 1000 | 8980 | 30.0 | 1660 | 141 | 140 | 71 | 71 |
| | 2000 | 9030 | 29.2 | 1560 | 139 | 139 | 70 | 70 |
| | 3000 | 9040 | 29.6 | 1500 | 139 | 139 | 70 | 70 |
| | 4000 | 9000 | 30.4 | 1520 | 140 | 140 | 70 | 71 |
| | 5000 | 8800 | 31.8 | 1700 | 136 | 137 | 72 | 72 |

* Data for train gyro rotor bearing No. 1 and elevation gyro rotor upper bearing.

** Data for train gyro rotor bearing No. 2 and elevation gyro rotor lower bearing.

in intensity were found at 550, 600, 850, and 1700 cps. The principal frequency peak of about 700 cps showed little change during the period of operation of the gyro.

After completion of the test, the Gun Sight Mark 15 "D" gyros were held on the shelf for approximately one year before disassembly for examination of the bearings. The grease appeared to be quite soft. Some cracking of the lubricant was noted near the outer race of train gyro bearing No. 1 and here the grease was somewhat harder. However, the interior of the bearing appeared to be adequately covered by lubricant. Some of the grease on the balls and that near the races exhibited a pinkish tint and several red particles were found on the surface of the grease in train gyro bearing No. 1. The source of this red material was not determined but it had not been observed in any other bearings lubricated with the same grease. It is assumed that it entered the bearings by means of the air stream during operation of the gyros. Inspection of the train gyro bearings indicated very little wear had taken place although the ball track of bearing No. 1 appeared to be rather wide. The elevation gyro bearing wear appeared to be slightly greater than that observed on the train gyro bearings. However, the original finish of the upper bearing outer race appeared to be somewhat inferior to that of the other bearings. All the balls appeared to be in good condition and corrosion, if any, was very slight. However, it was possible to see light wear circles. The pressed steel retainers appeared to be in good condition. It was obvious that these bearings could have operated without failure for considerably longer.

Operating data on the third set of gyros designated as the "E" group lubricated with the copper phthalocyanine-diester grease will be found in Table 6. Some difficulty was experienced in rotor speed stability at the time of setting the air nozzles at the beginning of the test. Although this condition persisted for several hundred hours of operation, by the end of the test the speed of the train gyro rotor had dropped less than that of any of

TABLE 6
Operation Data on the Gun Sight
Mark 15 Gyros With Experimental CPC Grease

| Gyro | Operation (hr) | Rotor Speed (rpm) | Deceleration (sec) | 900-rpm Coast Time (sec) | Bearing Temperatures (°F) | | Bearing Noise Level (db) | |
|-----------|-------------------|-------------------------|-----------------------|--------------------------------|---------------------------------|-----|--------------------------------|-----|
| | | | | | A* | B** | A* | B** |
| TRAIN | 0 | 9020 | 28.6 | 740 | 140 | 140 | 78 | 77 |
| | 1000 | 9020 | 28.8 | 700 | 139 | 139 | 79 | 77 |
| | 2000 | 8990 | 29.7 | 600 | 140 | 140 | 79 | 78 |
| | 3000 | 8940 | 29.9 | 470 | 140 | 140 | 79 | 78 |
| | 4000 | 8900 | 29.9 | 310 | 142 | 142 | 80 | 80 |
| | 5000 | 8850 | 30.0 | 130 | 144 | 144 | 81 | 83 |
| ELEVATION | 0 | 9060 | 27.0 | 840 | 139 | 139 | 70 | 73 |
| | 1000 | 9060 | 28.2 | 840 | 138 | 138 | 77 | 77 |
| | 2000 | 9080 | 28.6 | 770 | 138 | 138 | 80 | 80 |
| | 3000 | 9020 | 28.9 | 600 | 138 | 138 | 80 | 81 |
| | 4000 | 8880 | 29.6 | 590 | 139 | 140 | 78 | 80 |
| | 5000 | 8640 | 31.5 | 100 | 143 | 143 | 76 | 72 |

*Data for train gyro rotor bearing No. 1 and elevation gyro rotor upper bearing.

**Data for elevation gyro rotor bearing No. 2 and elevation gyro rotor lower bearing.

the air-driven train gyros studied. Loss of speed amounted to only 1.9 percent. On the contrary, the elevation gyro rotor speed dropped 4.6 percent, the greatest loss in speed of all the rotors investigated. The drop in rotor speed was accompanied by a gradual increasing deceleration time. However, the 900-rpm coast times of both gyros steadily decreased. These coast-time curves were the most regular of those of all the air-driven gyros. Bearing temperatures did not show any significant trend, and the rise at the end of the test was a function of ambient temperature changes. The over-all noise level of the train gyro bearings gradually increased with operation. That of the elevation gyro bearings increased to a maximum at about 2000 hours and began to decrease rather rapidly during the last 1000 hours of operation as the rotor speed began dropping rather sharply.

Noise analysis spectra of the bearings of the "E" group were similar to most of those of the other air-driven gyros. Noise components from 380 to 1600 cps were found in the train gyro bearings with those most prominent and consistent appearing at approximately 380, 400, 450, 600, 700, 800 to 900, and 1200 cps. Most of the train gyro bearing noise peaks increased in intensity during the test, particularly those of bearing No. 2. A somewhat wider spread of frequencies was noted in analyzing the elevation gyro bearings, signals being recorded from about 220 cps to as high as 2300 cycles. Predominating peaks at 320, 450, 600, 700, 800, 1400, and 1500 were recorded. Following the same pattern as did the train gyro bearings, those in the elevation gyro were characterized by rather substantial increases in noise intensity at most frequencies. This was especially true of the upper bearing. No appreciable decrease in frequency intensity of this bearing was noted while noise of the lower bearing decreased only at 450, 700, and 900 cps as the test progressed.

In order to investigate the possible existence of noise at the higher frequencies, the "E" gyro bearings were studied with the barium titanate pickup. Comparison of the noise patterns of train gyro bearing No. 1 when using the vibration pickup and the accelerometer are shown in Figs. 11 and 12, respectively; while the same comparison of the elevation gyro upper bearing is given in Figs. 13 and 14. It is seen that in addition to the frequencies recognized by the vibration pickup, the accelerometer recorded many more. However, as mentioned previously, the frequencies observed below 100 cps when using the accelerometer should be disregarded. It should also be noted that the frequencies recognized by the vibration pickup were of lower intensity than those in the high-frequency region. This means that a high percentage of the total noise emitted by elevation gyro bearing was in the high-frequency range. In general, this condition was also found to exist in the Stable Element gyro bearings.

In order to ascertain the natural frequencies of structural parts of the Gun Sight Mark 15 gyros, a series of noise analyses were made in the usual way but with the rotors stopped. The gyros were struck with a hammer as was done in making resonant vibration tests of the Stable Element gyro. With the vibration pickup as the transducer, spectrum pictures were made in the train gyro bearing No. 1 position and an equal number in the elevation gyro upper bearing position. In all, 38 frequencies were observed over the range of 55 to 3200 cps despite the fact that the General Radio vibration pickup does not respond well above 2000 cps. About the same number of analyses were made with the accelerometer. As before, the record of the initial impact was ignored. A total of 41 frequencies from 180 to 7000 cps were observed. Every noise frequency found in the routine bearing noise analyses made with the vibration pickup during the 5000 hours of operation of the "E" gyros was represented in the list of resonant frequencies observed.

Some probable sources of excitation causing vibration of structural parts of the air-driven gyros have been considered. The gyro rotors revolved at the rate of 145 to 150 rps. Therefore, any eccentricity of the inner bearing race would result in a fundamental frequency of about 150 cps. Multiples of this value have been noted in making the routine analyses. Neglecting ball-raceway slippage, the bearing cages revolved at about 56 rps.

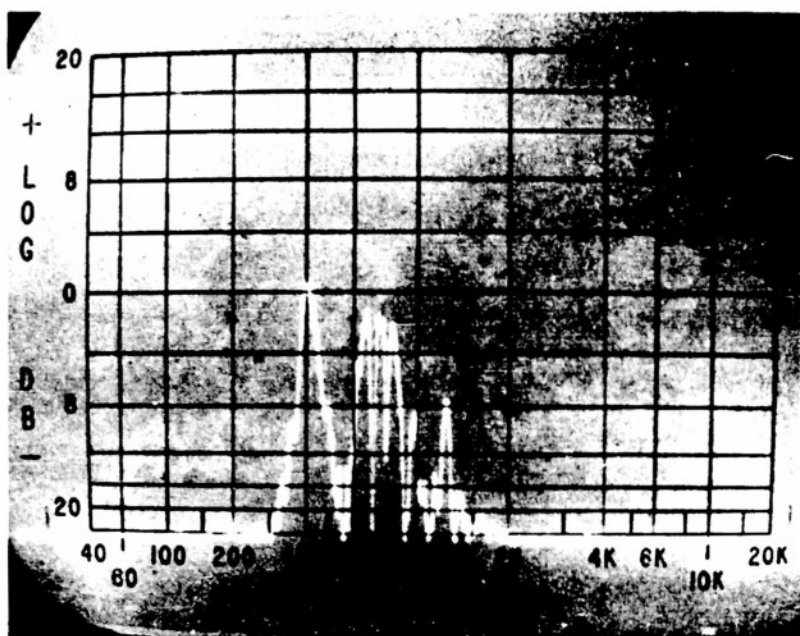


Figure 11 - Sound spectrum of Gun Sight Mark 15 "E" train gyro bearing No. 1. Hours of Operation: 5000; Lubricant: Copper phthalocyanine-diester grease; Zero \pm 80 decibels; Over-all noise level: 83 decibels. Vibration pickup used as transducer.

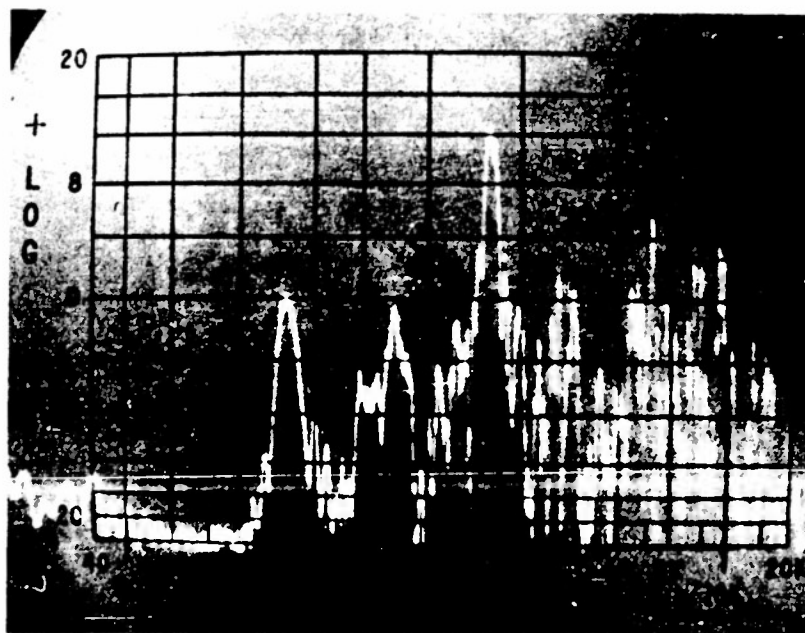


Figure 12 - Sound spectrum of Gun Sight Mark 15 "E" train gyro bearing No. 1. Hours of Operation: 5000; Lubricant: Copper phthalocyanine-diester grease; Zero \pm 78 decibels (at 1000 cps). Barium titanate accelerometer used as transducer.

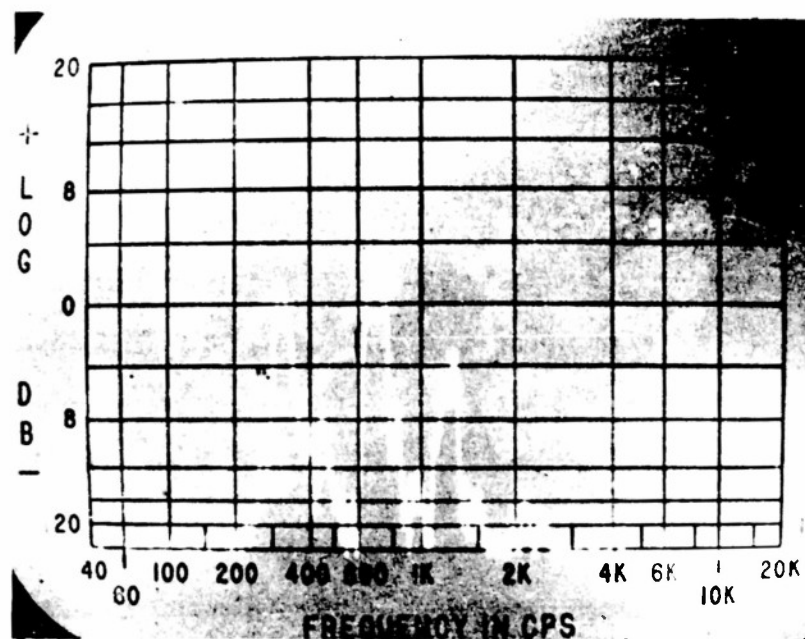


Figure 13 - Sound spectrum of Gun Sight Mark 15 "E" elevation gyro upper bearing. Hours of Operation: 5000; Lubricant: Copper phthalocyanine-diester grease; Zero \pm 70 decibels; Over-all level: 76 decibels. Vibration pick-up used as transducer.

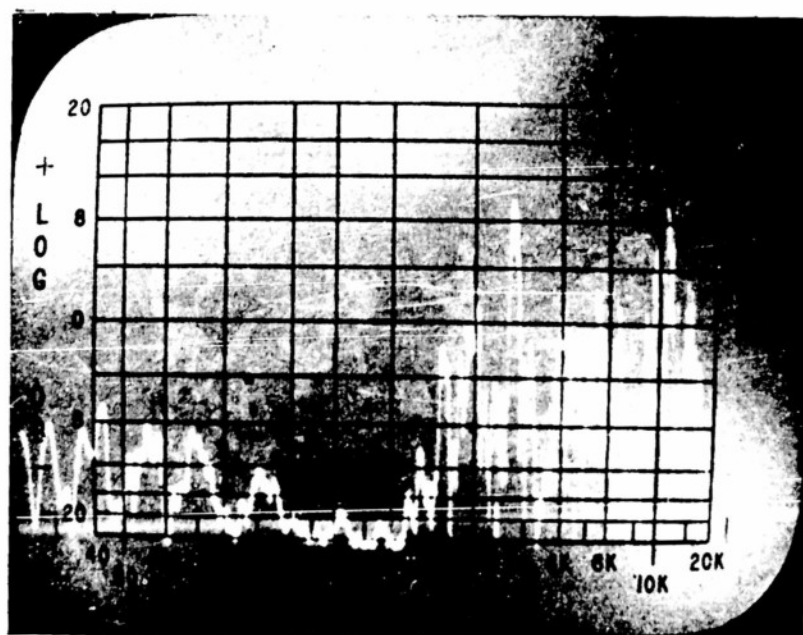


Figure 14 - Sound spectrum of Gun Sight Mark 15 "E" elevation gyro upper bearing. Hours of Operation: 5000; Lubricant: Copper phthalocyanine-diester grease; Zero \pm 78 decibels (at 1000 cps). Barium titanate accelerometer used as transducer.

For a single ball dent on the outer race, the revolving cage assembly would provide a fundamental frequency of about 392 cps when the 7 balls in each cage assembly are taken into account. Since the inner race turned 94 rps with reference to the bearing cage, a single ball dent on that race would give rise to a frequency of about 658 cps. It is obvious that additional roughness of either races or balls could give rise to a multitude of new frequencies. If the number of buckets on the rotor rims are considered, a frequency of 12,000 cps might be anticipated at a rotor speed of 9000 rpm. However, no differences in the noise spectra were observed when the air supply was momentarily cut off.

After the Gun Sight Mark 15 "E" gyro test had been completed, the gyros were held on the shelf for a period of eleven months before being disassembled for examination of the bearings and lubricant. The copper phthalocyanine grease appeared in general to be much like the original. However, a portion of that near the edge of the outer race of the elevation gyro lower bearing was rather black suggesting that it might contain wear particles. Further examination confirmed this was the case. This condition was not observed in the other bearings. Examination of the elevation gyro lower bearing revealed that this bearing was of inferior quality even when new as compared to the other bearings used. The operating surface of the outer race was definitely substandard as shown by very rough grooves and a wavy surface even in the area outside the ball tracks. While the original finish of the inner race was better, several fatigue pits were found in the ball track. In addition, the wear tracks of this bearing were the most pronounced of all those observed. The balls had obviously been damaged as a result of operating over the fatigue pits. On the other hand, the elevation gyro upper bearing was in reasonably good condition.

The finish of the train gyro bearings appeared to be of high quality and the bearings were in good operating condition. The wear tracks of all the bearings lubricated by the copper phthalocyanine grease were brown in color, particularly in the abraded portion. This brown coloration or coating was observed on the balls as well. In every case, each ball was covered with this coating although the smooth surface of the metal could be seen through the brown coloration. This coating could not be readily removed by scraping and may possibly have been a very thin oxide coating. A lighter but similar coating has been observed previously on bearings used with other lubricants. The pigment in the copper phthalocyanine grease tended to adhere tightly to the metal surfaces, particularly on the surface of the races adjacent to the ball tracks. Since the train gyro operated the most satisfactorily of all the air-driven gyros studied, the presence of this coating would not appear to be detrimental. It was evident that the train gyro bearings and possibly the elevation gyro upper bearing would have operated for a considerably longer time. However, it was obvious that the poor operation of the elevation gyro rotor was due to the approaching failure of the lower bearing.

Power Supply Equipment

The Motor-Generator Mark 5 Mod 0 used for driving the Gun Sight Mark 20 gyros operated satisfactorily for 10,000 hours with Union Oil Company Red Line Z-801 grease as the bearing lubricant. The Motor-Generator MG-145 used for driving the Stable Element was operated for a total of 18,000 hours with the same lubricant. The air supply units BuOrd No. 417054-1 used for driving the Gun Sight Mark 15 gyros were far more trouble-free than when used in the previous work (7, 8). While the valves continued to fail every 2000 to 3000 hours, the use of neoprene rubber piston diaphragms, developed by this Laboratory and introduced in the earlier runs, has resulted in relative freedom from undue diaphragm failures. As mentioned in previous reports (7, 15), the lubricant in the connecting rod ball bearings supplied from BuOrd stock have been unsatisfactory. During the current study, this lubricant has been replaced with Texas Company TG-1819 high temperature grease and has given excellent results. This lubricant is of the type available under Specification MIL-L-3545 (formerly AN-G-5a) (16).

Gunar Mark 31 0.1 Fg 2 Gyros

The three Gunar Mark 31 0.1 Fg 2 gyros were designated as C-31, C-32, and C-35. Prior to installation of the gyros in the cases, certain coast-time tests were made on them to establish the value of subsequent coast-time data with reference to changes in bearing preload. As mentioned earlier, the degree of preload on the rotor bearings was controlled by the thickness of the spacers between the inner and outer bearing races. In assembling these gyros, the bearing inner races, spacers, and stator assembly were all secured by a steel shaft. The gyros were attached to the cases by means of this same shaft, the whole assembly being tightened by means of a nut on the end of the shaft. It was determined during disassembly of the gyros that this nut had been tightened to approximately 50 inch-ounces. Coast-time data taken with the shaft nut tightened from 20 inch-ounces to 90 inch-ounces torque indicated that despite the spacers, the coast time gradually decreased as the nut was tightened. Gradually loosening the nut caused the opposite effect. This change of about 10 percent in coast time was sufficient to warrant carefully setting the shaft nut at 50 inch-ounces when the gyros were installed in the cases.

In order to obtain more information regarding the relation of coast time to preload, the inner spacer of the C-32 gyro was temporarily removed and the bearings preloaded directly by means of dead weights. As expected, increasing the preload from 0.1 pound to 2 pounds caused a decrease in coast time; the opposite resulted when the preload was decreased. Subsequent tests indicated that at any given preload over the range of 0.5 pound to 2 pounds, coast times were reproducible within about 10 percent. It was found that the coast-time tests were very sensitive to temperature, and the above data was dependent on careful control of the gyro operating temperature. When the C-32 gyro was reassembled, the coast time obtained was within 10 percent of that obtained previously by direct preloading to 1-3/4 pounds. However, when the gyro shaft was rotated to certain positions and tightened, the gyro refused to start. This was obviously due to distortion within the bearing assembly and demonstrated the extreme care required in controlling the dimensions of the spacers and bearings during manufacture.

After the bearing retainers of the C-32 and C-35 gyros had been impregnated with 14-0-20 oil as described earlier, the assembled gyros were placed in the small cases. Prior to filling with helium, all three gyro cases were evacuated and then flushed with dry oil-free helium and evacuated. This process was repeated several times before the admittance tubes were finally sealed and the cases tested for leaks under hot water.

The C-31 gyro lubricated with petroleum oil was operated for 10,000 hours. As shown in Table 7, the operating data for the first 2000 hours were characterized by a gradual increase in coast times, bearing temperature, bearing noise, and a slight increase in power consumption. At this point, the coast-time curves dropped abruptly reaching a minimum at 2500 hours while the bearing noise level attained a maximum at the same time. At this point, increased bearing noise characterized by a rasp or rattle could be detected by ear. (This noise persisted for the duration of the test, and it increased in intensity appreciably if the gyro was temporarily removed from the oven and allowed to cool down. The noise subsided when the gyro temperature rose.) By the time 3000 hours of operation had been reached, both coast times had reached new maximums, and bearing noise had reached a minimum. No additional sudden changes in the gyro operating characteristics occurred during the remainder of the test. Both coast times gradually declined to 5000 hours and increased again to an all high at about 7500 hours. They were again decreasing at the time the test was stopped. While changes in bearing temperatures were small, a gradual decrease in temperature was noted from the high at about 2000 hours. After the bearing noise level reached a minimum at about 3000 hours, it gradually increased until at the end of the test it again stood at the same level as the previous high at 2500 hours. As might be expected, the characteristics of

TABLE 7
Operating Data on the Gunar
Mark 31 Gyro C-31 With Teresso V-78 Petroleum Oil

| Operation (hr) | Total Coast Time (sec) | 1000-rpm Coast Time (sec) | Bearing Temperature (°F) | Bearing Noise Level (db) | Power (watts) |
|----------------|------------------------|---------------------------|--------------------------|--------------------------|---------------|
| 0 | 63 | 9.* | 206 | 78 | 5.0 |
| 1000 | 80 | 9. | 208 | 80 | 5.2 |
| 2000 | 87 | 12. | 209 | 81 | 5.2 |
| 2500 | 65 | 5. | 209 | 83 | 5.4 |
| 3000 | 111 | 17.0 | 208 | 78 | 5.2 |
| 4000 | 103 | 14.1 | 206 | 78 | 5.1 |
| 5000 | 100 | 14.0 | 205 | 79 | 5.0 |
| 6000 | 102 | 14.2 | 204 | 81 | 5.0 |
| 7000 | 112 | 18.4 | 203 | 81 | 4.8 |
| 8000 | 119 | 19.6 | 202 | 81 | 4.8 |
| 9000 | 115 | 19.2 | 202 | 82 | 4.8 |
| 10,000 | 108 | 17.4 | 202 | 83 | 4.8 |

* After 150 hours of operation

the power consumption vs time curve were very similar to those of the bearing temperature vs time curve.

It was of interest to note that the characteristics of the total coast-time curve and that of the 1000-rpm to 0-rpm curve were almost identical. This would seem to indicate that the friction at high speeds was comparable to that at low rotational speeds. This might be expected since the gyro had a small rotor and was operating in an atmosphere of a low density gas with reduced windage losses as compared to the same gyro operating in air.

Analyses were made periodically of the bearing noise using both the General Radio vibration pickup and the barium titanate accelerometer in connection with the Panoramic Sonic analyzer. At the beginning of the test a relatively simple noise spectrum was observed. Frequencies observed were those at 170, 210, 480, 950, 1100, 1400, and 1500 cps. However, spectra photographed at the time of the sudden change in operating characteristics included new noise peaks at 550, 600, 700, 750, 800, 900, and 1000 cps (Fig. 15). By the time 4000 hours of operation had passed, additional noise was observed at 300, 320, 380, 400, and 1200 cps. Few additional frequencies appeared at the end of the test, but most of those observed earlier were still present (Fig. 16). It was of interest that all the noise frequencies observed at 2430 hours dropped to a minimum at 4000 hours with the exception of the noise at 210 and 600 cps. However, noise at the principal frequencies had increased in intensity by the end of the test.

Acoustical spectra obtained with the accelerometer were similar to those observed with the vibration pickup over the comparable frequency response range. However, in addition to the noise peaks observed previously, others were seen (Fig. 17) at 1600, 1800, 2000, 2200, 2500, 2600, 2800, 3000, 3400, 3800, 5800, 6000, 6500, 14,000, and 18,000 cps. Most of these frequencies had appeared by the time 2500 hours of operation of the gyro had passed, had reached a minimum in intensity at 4000 hours, and had again increased by the end of the test.

The C-31 gyro case was opened for inspection at the end of the test. The rotor turned freely by hand, and the "feel" of the bearings was reasonably smooth. However, there appeared to be a very slight amount of radial play in the bearings. This may have

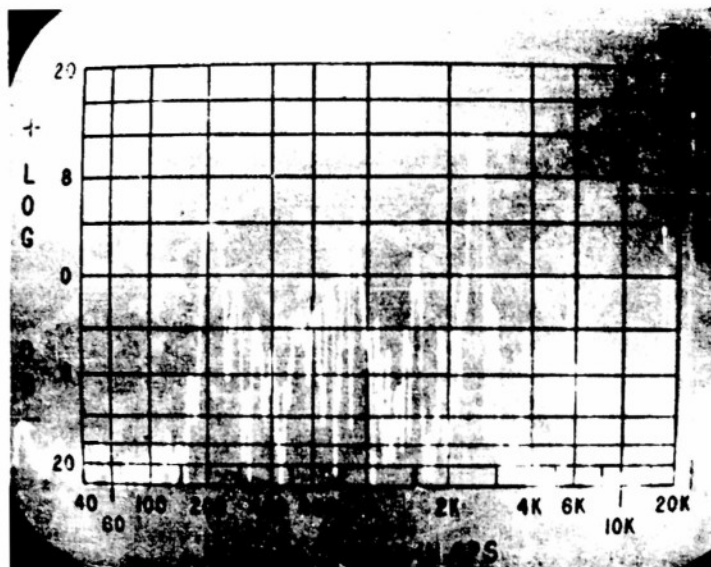


Figure 17 - Sound spectrum of Gunar Mark 31 Gyro C-31. Hours of Operation: 10,000 hours; Lubricant: Teresso V-78 petroleum oil; Zero \pm 78 decibels (at 1000 cps). Barium Titanate accelerometer used as transducer.

partially accounted for the rattling sound which could be heard when the rotor was turned by hand and when the gyro was operating. A brown varnish-like coating had been deposited on the inside of the case. It was not readily soluble in any of the ordinary organic solvents. There was no deposit on the rotor and very little on the stator assembly. However, a rather heavy deposition had occurred on the thermocouple clamp and clamp screw. Tests indicated that this material originated principally from two replacement power leads and from tape installed in the gyro prior to sealing the case. The insulating materials were not sufficiently thermostable under the conditions encountered. When the shaft and stator assembly was removed, a deposit of dry green powder was found around the edges of the bearing outer races. The bearings were dry and appeared to be devoid of lubricant. The exposed surfaces of the bearing spacers were covered with a greenish film somewhat vitreous in appearance. This film or coating appeared to consist of particles of the green material just noted which appeared to have been cemented down by the solidification of a liquid phase. The coating could be scraped off, however, and the scrapings were rather yellow in appearance. The surfaces under the coating were rather dull and had been lightly etched. This same surface condition was observed on the bearings when they were cut open for examination. However, the balls and races did not reveal the presence of any fatigue pits or other indication of serious wear. It was evident that some wear had occurred on the outer races, possibly enough to destroy the preload. This would leave the bearings very lightly loaded and was probably one reason why the gyro continued to operate so long beyond this point.

The "Synthane" retainers exhibited evidence of wear particularly where rubbing occurred between the retainers and the bearing inner races. While there was little indication of magnetic material in the bearing dust, chemical tests revealed some iron to be present. Treatment of the dust with concentrated hydrochloric acid left a residue which was nearly colorless. Examination of this material under the polarizing microscope indicated it was a brilliantly birefringent substance containing fragments of thin films or plates. Further examination of the dust confirmed that it was composed of wear products from the retainers, particles of solidified lubricant, and a small amount of iron wear products.

When the C-32 gyro was placed into operation, it was apparent that both the bearing temperature and power consumption were higher than that experienced with the C-31 gyro. That these conditions persisted throughout the test may be seen in the operating data given in Table 8. The test was continued for approximately 1600 hours when the gyro refused to start after making a routine coast test. Subsequent attempts to start the unit were unsuccessful.

TABLE 8
Operating Data on the Gunar
Mark 31 Gyro C-32 With Specification (ORD) 14-0-20 Oil

| Operation (hr) | Total Coast Time (sec) | 1000-rpm Coast Time (sec) | Bearing Temperature (°F) | Bearing Noise Level (db) | Power (watts) |
|----------------|------------------------|---------------------------|--------------------------|--------------------------|---------------|
| 0 | 58 | 14.8* | 224 | 77 | 7.6 |
| 200 | 93 | 16.2 | 221 | 85 | 7.2 |
| 400 | 98 | 17.6 | 219 | 85 | 6.9 |
| 600 | 96 | 16.8 | 218 | 85 | 6.9 |
| 800 | 97 | 17.0 | 218 | 85 | 7.2 |
| 1000 | 100 | 18.0 | 218 | 85 | 7.4 |
| 1200 | 98 | 16.1 | 218 | 85 | 7.4 |
| 1400 | 90 | 15.0 | 220 | 85 | 7.3 |
| 1600 | 35 | 1.4 | 221 | 87 | 7.2 |
| | | | | | 8.9** |

*After 150 hours of operation

**Stalled rotor

After considerable fluctuating during the first 100 hours of operation, the coast time gradually rose and remained reasonably constant for 1200 hours before it began to decrease appreciably. During the last 200 hours, the curve dropped sharply. The 1000-rpm to 0-rpm coast-time curve behaved very much in the same way. Bearing temperatures decreased during the course of the test but were beginning to rise when the test was completed. The power consumption vs. time curve was similar in the early part of the test, but the demand for power began to increase at about 800 hours. Bearing noise level fluctuated considerably during the first 50 hours of operation, and increased to a value of 85 db at about 100 hours and remained at this level until the latter part of the test.

Bearing noise spectra photographed at the start of the test were more complex than those observed early in the operation of the C-31 gyro. Most of the noise appeared at 170, 190, 210, 320, 350, 380, 400, 480, 600, 700, 800, 850, 900, 1000, 1200, 1300, 1400, 1500, and 1600 cps. A majority of these frequencies persisted throughout the test (Fig. 18) and merely increased very gradually in intensity. Unlike the C-31 gyro spectra, very few new frequencies appeared during the course of the run.

When the gyro case was opened after the test, only a very light waxy coating was found on the inside walls of the container. The thermocouple clamp assembly and thermocouple wire were covered with a brown varnish-like deposit apparently from the lubricant. The rotor could be turned by hand, but the bearing action was rough. The radial play in the rotor assembly was more pronounced than that observed in the C-31 gyro. Upon removing the bearings, a rather generous deposit of reddish-brown powder or dust was observed around the edges of the bearing outer races and on the inside of the rotor shell. The bearings were very dry and the clearances were filled with the dust.

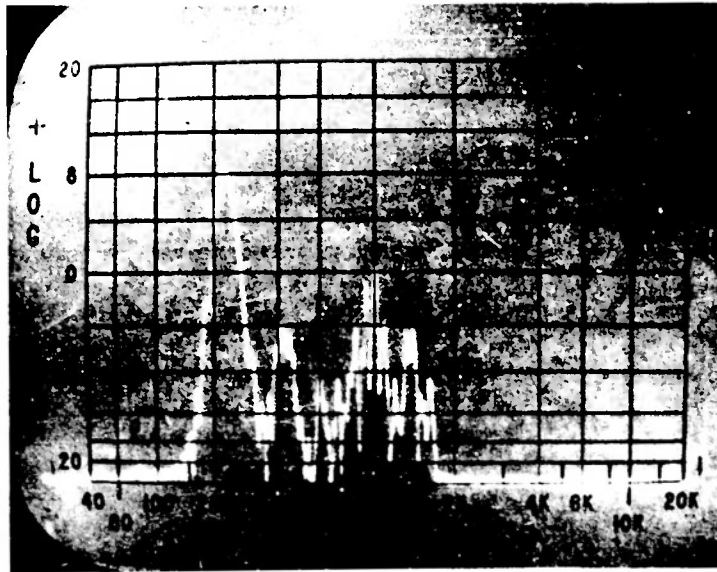


Figure 18 - Sound spectrum of Gunar Mark 31 Gyro C-32. Hours of Operation: 1500; Lubricant: Specification 14-0-20 oil; Zero \pm 80 decibels. Vibration pickup used as transducer.

However, when the bearings were opened, the surfaces were quite bright except for layers of lacquer adjacent to the raceways. It was difficult to determine the amount of wear, but there were no evidences of failure of the contact surfaces. Examination of the retainers revealed a varnish-like coating which was particularly heavy around the ball holes and much more pronounced than that observed on the C-31 gyro retainers. More wear was evident on the inside of the retainers than had been observed previously. The bearing spacers were covered with dust, but the coating could be easily brushed off leaving the surfaces quite bright.

Examination of the bearing dust under the inspection microscope revealed it to be a granular material containing flakes or fibers. It was birefringent and magnetic, and presumably the iron was a magnetic iron oxide. Iron in this form has been found as a wear product in other studies in ball bearing lubrication (17). The presence of iron was confirmed by chemical tests. Although the gyro was operated in a helium atmosphere, it was possible that small amounts of oxygen were present in the system. Thus the appearance of iron oxide as a wear product was not unexpected. Additional examination of the dust proved it to be made up of wear particles from the bearing contact surfaces and retainers mixed with particles of pulverized lacquer from the deterioration of the lubricant. It was apparent that the excessive amount of this dust in the dry bearings interfered with the rolling action of the balls, preventing starting of the gyro.

Due to the abnormal operation of the C-32 gyro, it seemed desirable to make an investigation of the C-35 gyro using 14-0-20 oil as the lubricant. Unlike the C-32 unit, this gyro had not been used in the preliminary experiments and save for the disassembly during the lubrication process described earlier, it was placed under test with a minimum of preliminary operation. Data obtained during the operation of this unit is given in Table 9. Operation was continued for approximately 1080 hours when the gyro refused to start after making a routine coast test. Unlike the C-32 gyro, the coast time did not fluctuate early in the test but increased to a maximum at about 400 hours and then gradually decreased to the end of the run. The low-speed coast-time curve behaved

TABLE 9
Operating Data on the Gunar
Mark 31 Gyro C-35 With Specification (ORD) 14-0-20 Oil

| Operation (hr) | Total Coast Time (sec) | 1000-rpm Coast Time (sec) | Bearing Temperature ($^{\circ}$ F) | Bearing Noise Level (db) | Power (watts) |
|----------------|------------------------|---------------------------|-------------------------------------|--------------------------|---------------|
| 0 | 63 | 9.2 | 210 | 78 | 5.3 |
| 200 | 84 | 11.8 | 202 | 81 | 5.5 |
| 400 | 86 | 14.2 | 202 | 83 | 5.6 |
| 600 | 85 | 14.4 | 204 | 84 | 5.7 |
| 800 | 80 | 14.0 | 206 | 85 | 5.6 |
| 1080 | 74 | 13.8 | 204 | 86 | 5.3 |
| | | | | | 8.4* |

*Stalled rotor

similarly. After an initial high of 210° F, bearing temperature dropped to 202° F, and only minor changes occurred beyond that point. In contrast, power consumption increased during the course of the run but had returned to the original value by the time the test had stopped.

Noise spectra recorded at the beginning of the test were more like those of the C-31 gyro. Noise was emitted at 170, 190, 210, 600, 800, 900, 1000, 1300, and 1500 cps. By the time 200 hours had been reached, new frequencies of 380, 400, 450, 520, 700, 950, 1200, and 1400 cps appeared. These frequencies persisted and increased in intensity until the test was concluded (Fig. 19).

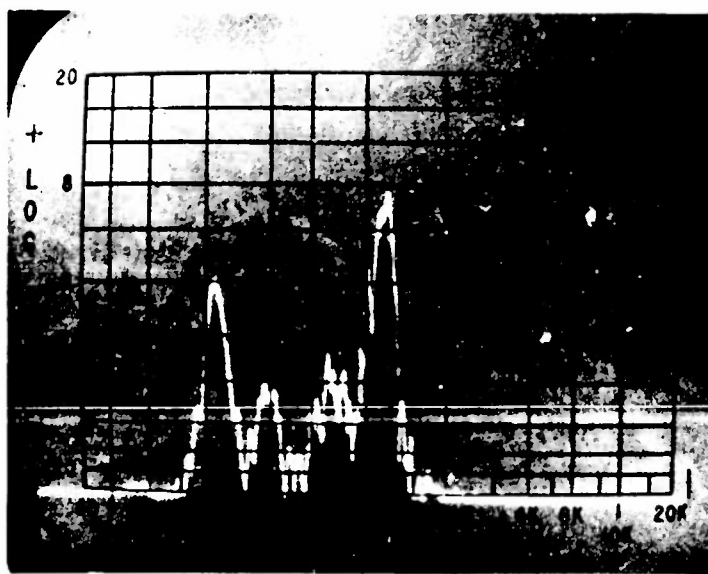


Figure 19 - Sound spectrum of Gunar Mark 31 Gyro C-35. Hours of Operation: 1080; Lubricant: Specification 14-0-20 oil; Zero \pm 80 decibels. Vibration pickup used as transducer.

When the C-35 gyro case was opened, the thermocouple clamp was found broken although enough of the clamp remained to hold the thermocouple against the gripping ring. The smaller part of the clamp, which was still attached to the clamp screw, rested lightly against the rotor. It was obvious, however, that this condition was not the cause of the failure since the gyro had been operating in this fashion for some time. The inside of the case contained a somewhat heavier coating of waxy material than was found in the C-32 gyro case. In contrast, the varnish film on the thermocouple clamp assembly was less pronounced than had been observed on the C-32 gyro. The rotor had excessive radial play, and the bearing action was rough when the rotor was turned by hand. Further disassembling of the gyro revealed additional varnish deposits similar to those observed in the other gyros. An even more generous amount of dusty material was found adjacent to the bearing outer races and on the inside of the rotor than had been seen thus far. However, this powder was dark brown in color. The bearings were devoid of lubricant and the clearances were pretty well filled with the powder. Some lacquer had formed on the inside of the rotor, and the radial play in the bearings had apparently been sufficient to cause some scuffing of the lacquer coating against the gyro stator.

Examination of the bearings did not show any indication of imminent failure but it was apparent that the bearing contact surfaces had been lightly etched. Lacquer deposits on the retainers were less pronounced than those found in the C-32 gyro, but the edges of the retainers were rather brittle and apparently some flaking of the material had occurred. Upon brushing the bearing dust from the spacers, it was seen that the surfaces were still bright but were lightly etched. The dust contained more magnetic iron oxide than that from the C-32 gyro. Treatment of the material with concentrated hydrochloric acid dissolved the iron oxide and left a nonmagnetic light yellow residue which proved to be a mixture of a fibrous birefringent material and a nearly isotropic substance. It evidently originated from the retainers and from the polymerized lubricant. The magnetic iron oxide in the dust was a product of iron oxidation occurring during bearing wear as mentioned earlier (17). It was evident that the gyro refused to start because of the interference of the dust with the rolling action of the balls. It is probable that if both the C-32 and C-35 gyros had been disassembled and the bearings cleaned and lubricated the gyros would have continued to operate for a time.

As had been suggested in earlier gyro reports (7, 8), many of the noise peaks observed in noise analyses studies were probably due to resonant vibrations of structural parts of the gyro. In order to obtain information regarding the natural frequencies of the Gunar gyro assemblies used in the tests, a series of spectra were photographed while the gyro cases were struck lightly with a small steel hammer as was done in obtaining the same type of information on the heavier shipboard gyros. Use was made of the General Radio vibration pickup in the observation of 21 natural frequencies from 170 to 4200 cps out of a total of 26 spectra studied. When the accelerometer was substituted for the vibration pickup, 35 frequencies over the range of 150 to 12,000 cps were recorded out of a total of 31 spectra studied. Of the approximately 36 principal or most frequently occurring frequencies observed during the routine vibration spectral analyses of the gyros, 25 were included in the total list of 39 natural or resonant frequencies.

Factors in the design or operation of the Gunar gyros which might have been responsible for some of the frequencies observed or which were involved in exciting parts of the gyros to resonance have been considered. As mentioned earlier (7, 8), some of the characteristics of the noise spectra may have been due to electrical stresses within the gyro rotor or stator (14). Thus the power frequency of approximately 400 cps may have been responsible for this frequency appearing in some of the noise spectra. The frequency of about 210 cps, which appeared so prominently in all the noise spectra, was very likely that of the rotor speed in rps. This would mean that the rotors were actually operating at about 12,600 rpm instead of the original 12,000 rpm observed by means of the Strobotac while the gyros were running in air. The resonant frequency of the vibration pickup would tend to influence a frequency appearing in the neighborhood of 1500 cps (12).

A study of the rotational speed of the rotors and bearing components indicated that since the rotors revolved at 200 to 210 rps, any eccentricity of the bearing outer races would produce a fundamental frequency of 200 to 210 cps. The bearing retainer assembly rotated at about 125 to 131 rps if ball slippage is neglected. By taking into account the 8 balls in each bearing, a single ball dent on the inner bearing race could have been responsible for a fundamental frequency of 1000 to 1050 cps. Since speed of the outer race was about 75 to 79 rps with reference to the bearing retainer assembly, a single dent in the bearing outer race would give rise to a frequency of 600 to 630 cps depending on the exact speed of the rotor. With a combination of many raceway and ball defects, the bearings could be expected to serve as excellent exciters for all the natural frequencies known to exist in the gyro assemblies.

CONCLUSIONS

Operation of the Gun Sight Mark 20 gyros with both Specification (ORD) 14-0-20 oil and MIL-G-15793 grease for 10,000 hours has been satisfactory. Examination of the rotor bearings after over a year of storage following the tests indicated that these lubricants provided adequate lubrication and protection for these bearings.

Lubrication of the Stable Element Mark 6 gyro with these diester-type lubricants was satisfactory. However, it is imperative that the level of the lubricating fluid in the lower reservoir be maintained at a higher level than specified when using the diester oil. This will be assured if the level is determined with the gyro in a horizontal instead of a tilted position.

The study of the Gun Sight Mark 15 gyros using these synthetic lubricants revealed some reduction of rotor speed as the tests progressed. However, this condition was also characteristic of the air-driven gyros which were lubricated with petroleum oil (7, 8). In consideration of the fact that those tests were conducted at about 80°F instead of 140°F, it is likely that more severe volatilization of the petroleum oil would have occurred at higher operating temperatures resulting in even lower rotor speeds by the time the tests had ended. It is believed that the synthetic lubricants used were more suitable than the Teresso 43 oil used earlier.

Of the diester lubricants used, the Specification (ORD) 14-0-20 oil proved more successful than the grease from the standpoint of rotor speed stability and over-all bearing noise characteristics. However, examination of the bearings indicated that under storage conditions the oil-lubricated elevation gyro bearings may become rather dry, a condition which will invite corrosion and early bearing failure. Rotor speed stability of the gyros lubricated with MIL-G-15793 grease was not quite as satisfactory but bearing noise characteristics, coast-time data, and examination of the bearings after the test was completed and the gyros had been stored showed no indication of imminent bearing failure.

The question of suitability of the experimental copper phthalocyanine-diester grease used in lubricating the "E" gyros is somewhat obscured in light of the operating characteristics of these units. Here the train gyro rotor speed stability was superior to that of all the train gyro rotors studied, while the elevation gyro rotor speed dropped below that of any of the elevation gyros investigated. This was opposite in effect to conditions noted in the other air-driven gyros in that the elevation gyro rotor speed stability was usually superior to that of the train gyros. Since the noise levels of the "E" elevation gyro bearings increased much more rapidly early in the test as compared to the "E" train gyro bearing noise, it was indicated that at least one of the elevation gyro bearings was inferior to those used in the other gyros. Examination of the bearings after the test had been completed revealed this to be the case. The inferior elevation gyro lower bearing was undoubtedly the cause of the increase in noise level and the poor operation of that gyro. The condition of the other bearings in the "E" gyros would seem to indicate that

the copper phthalocyanine-diester grease provided adequate lubrication and protection during limited storage. While it is concluded that the brown coloration of the balls in the bearings lubricated with this grease was not detrimental to satisfactory operation for the length of time covered by the tests, complete evaluation of this grease as a gyro lubricant will require longer tests on a larger number of gyros.

The results of the tests of all the gyros with the three types of diester lubricants have indicated that from an over-all standpoint the MIL-G-15793 instrument grease is the most satisfactory lubricant.

At the time the gyro studies were begun, no shielded bearings of the proper quality and size were available. Therefore, all the bearings used, including those lubricated with grease, were of the open type. It is obvious that in the commercial production of grease-lubricated gyros the rotor bearings would be provided with some type of shielding. This would assure better retention of the lubricant and minimize contamination of the bearing with foreign material during manufacture, operation, or overhaul. The importance of bearing cleanliness in maintaining the original precision cannot be overemphasized particularly in lightly loaded instrument bearings where deterioration of certain operating characteristics may become apparent before serious deterioration of the bearings takes place (18). In addition to the conventional dimensional, surface finish, and cleanliness inspections, the bearing manufacturer will have the responsibility of properly lubricating the bearing. This will entail not only the final cleaning of the bearing, but the necessity of making certain that the lubricant is very clean. This is fully as important as initial bearing cleanliness. Thus it is seen that final bearing inspection must be even more rigorous than for the open type since the bearing cannot be cleaned before being put into use.

Operation of the Motor-Generators Mark 5, Mod 0 and Type MG-145 with Union Oil Company Red Line Z-801 grease and the air supply units with Specification MIL-L-3545 grease shows that these lubricants are satisfactory. It is further concluded that the satisfactory operation of the air supply units is contingent upon the use of grease of this type in the connecting-rod ball bearings.

Although the Gunar C-31 gyro continued to operate for 10,000 hours, it was evident that very serious changes occurred after about 2500 hours. It is concluded that the only reason the gyro continued to operate was that all, or a major part, of the preload had been destroyed and had left the gyro bearings very lightly loaded. This condition may have permitted sufficient shifting of the rotor to render the gyro unsuitable for use in high-precision computing mechanisms. Since the C-32 and C-35 gyros had a very short useful life, it was obvious that the Teresso V-78 petroleum oil was more suitable than the diester-type 14-0-20 oil as applied to the Gunar gyros.

It was evident that despite the much longer operating period of the C-31 gyro as compared to the other two, bearing wear was less. This may have been due to the lubricating effect of a heavier residue remaining after the more volatile compounds of the petroleum oil had left the bearings. On the other hand, since the 14-0-20 oil was a relatively pure compound, no residue was left to give marginal lubrication after the lubricant had evaporated or had been absorbed by the bearing dust being formed. This situation might be alleviated by blending a small amount of a much less volatile lubricant with the 14-0-20 oil. The need for inclusion of antiwear additives in the diester fluids intended for use in these gyros is also indicated by the relatively high wear rates found here.

After the 14-0-20 oil had disappeared from the C-32 and C-35 bearings, it was obvious that increased wear of bearings and retainers occurred and resulted in more dust in the bearings than was found in the C-31 gyro bearings. It is believed that continued operation of the C-31 gyro would have produced much the same result as that which occurred with the 14-0-20 oil in a shorter time. With the 14-0-20 oil sufficient

bearing wear had occurred to produce magnetic iron oxide, but since the bearings had not begun to fail badly, no free iron was found in the bearing dust.

It is obvious that additional information regarding the oil absorption properties of materials suitable for use as ball bearing retainers is needed. The amount of lubricant taken up by the bearing retainers used in the Gunar gyros was not known. However, the quantity absorbed by these retainers would be dependent on the amount and type of filler used with the phenolic resin and also upon the condition of the surface of the retainer. It is unlikely, however, that the absorption of oil amounted to more than a few percent.

The method of providing preload of the Gunar gyro bearings required extreme care in manufacturing and in assembling the gyros. It is concluded that a system whereby the bearing inner race could align itself with the outer race upon assembly would result in less rigid manufacturing requirements, and it might improve the operation of the bearings.

It is believed that the use of helium as an atmosphere in which to operate small high-speed gyros, as had been suggested earlier (7, 8), is desirable from the standpoint of reduced windage losses. The effect of the inert gas on bearing wear characteristics and lubricant stability has not been established.

It is concluded that neither of the two lubricants used was entirely satisfactory as lubricants for the Gunar gyros and that additional study of the problem from the standpoint of mechanical design and the choice of retainer material and lubricants is indicated.

Results of the long runs made on the various gyros have shown certain operating characteristics to be most significant as criteria of rotor bearing condition. The rotor speed stability of the air-driven gyros, under the operating conditions established, was a function of the degree of friction in the rotor bearings. This phenomenon, peculiar to air-driven gyros, is recognized by others (19). The bearing friction involved not only the physical condition of the bearings, but it has been demonstrated (20, 21, 22) that the operation of ball bearings at high speeds may introduce many other factors influencing friction within the bearing. Centrifugal forces acting on the balls, changes in contact angles during operation, and high friction between balls and the retainer resulting in ball skidding may introduce additional frictional characteristics at the high speeds. However, with the relatively lightly loaded instrument bearings used in the gyro rotors, the bearing friction appeared to be quite small compared to windage loss due to the rapidly revolving rotors. Therefore, the time required for the rotors to drop 1000 rpm below operating speed did not appear to be a significant measurement. After the rotors had decelerated appreciably, the friction in the bearings became a much larger factor in determining the rate of deceleration. It is believed that the time required for the larger gyros to stop from 900 rpm or lower was more nearly a function of bearing friction. On the contrary, the 1000-rpm to 0-rpm coast-time curves of the Gunar gyros did not add much information to that supplied by the total coast-time data. This was probably due to the fact that the gyros were operated in a low-density atmosphere and that the rotors were only 1-1/2 inches in diameter, thus the windage losses were low as compared to the larger gyros operating in air. More specific information regarding low-speed friction in a rotor bearing may be obtained by using apparatus to measure the time required for a rotor to come to a stop from two or three rpm.

Preliminary studies of the Gunar gyros indicated that the use of total coast-time data as a means of determining a change in preload in the bearings could not be relied upon too closely. However, the over-all increase in coast times of the gyros as the tests progressed were far beyond the limits of reproducibility of the coast-time data for a given preload. A deterioration of the bearing surfaces would have introduced additional bearing friction and would have decreased the coast times. Observations of the gyros indicated that the bearing temperature exerted more influence on coast-time than

appreciable changes in preload values. However, the operating temperatures of the gyros did not vary widely during the tests, and even the variations observed were in the direction which would have decreased rather than increased the coast time. It is therefore concluded that the over-all increase in coast times observed during the course of the tests must have been due either to "wearing in" of the bearing surfaces, which reduced the bearing friction, or to marked reduction in bearing preload, or to both causes. Only at the very end of the tests did the coast times of the gyros begin to decrease, and this was probably due to the accumulation of wear products within the bearings.

A rise in the operating temperature of a ball bearing is usually considered an indication of imminent bearing or lubricant failure. However, with the relatively lightly loaded instrument bearings studied, it was apparent that initial bearing damage did occur without any noticeable temperature rise being recognized by the thermocouples. Thus, the typical bearing temperature "flashes" may only occur after some damage has been done near the end of the useful life of the bearing.

It is evident that the sound-level or vibration meter used with a suitable transducer is a valuable instrument for taking routine over-all bearing noise measurements when evaluating new bearings, when overhauling the equipment, or when conducting bearing life studies. However, the entire noise spectrum may cover a far wider range than that recognized by prod-type vibration pickups. It is desirable then that transducers which will respond to the entire audio-frequency range be used either in making over-all sound-level measurements or in making noise analyses. Therefore, the transducers must be attached mechanically to the piece of equipment being studied. This procedure will also serve to minimize errors which result from different techniques employed by more than one operator in holding the prod-type pickup.

This study of bearing noise reveals that most systems exhibit very complex noise spectra involving many factors in addition to the role played by the bearings. It is seen that the bearings act as exciters and that the various gyro components are involved in complex resonant frequency phenomena. This situation is further involved in that it is believed that considerable interexcitation between vibrating structural parts of the gyro exists. However, in spite of all this, it has been shown that each system exhibits a characteristic noise pattern which responds to changes in bearing condition. Thus, experience gained with an instrument such as the Panoramic Sonic analyzer may be very useful in the selection of new bearings during the manufacture or overhauling of equipment. Since the accelerometer has shown that noise in the upper part of the audio frequency spectrum exists, it is evident that additional study will be required to completely evaluate the relation of bearing condition to bearing noise phenomena. This may involve the study of noise in the ultrasonic region and should include the use of bearing testing equipment which would permit better control over structural resonance phenomena than that provided by conventional gyroscopic equipment.

RECOMMENDATIONS

1. Specifications 14-0-20 oil and MIL-G-15793 grease are recommended for lubrication of the Gun Sight Mark 20 gyro rotor bearings. The grease is preferred, however, because lubrication of the bearings is then necessary only upon overhaul of the gun sight while better protection against bearing corrosion is assured during storage of the equipment.

2. For lubricating the Stable Element Mark 6 gyro, Specification 14-0-20 oil may be used. However, it is imperative that a higher level of lubricant be maintained in the lower reservoir by servicing the lower bearing with the gyro in a horizontal rather than in a tilted position. Specification MIL-G-15793 instrument grease is more highly recommended, however, since the use of this lubricant will eliminate the need for servicing the

rotor bearings except during overhaul of the gyro and will provide better protection against bearing corrosion during storage.

3. Since the Gun Sight Mark 15 gyros are lubricated only at assembly, the use of MIL-G-15793 instrument grease is strongly recommended. For proper retention of the lubricant within the bearing and to provide better protection from contamination with foreign material during assembly or overhaul, the use of shielded rotor bearings is most desirable.

4. The increasing use of grease-lubricated ball bearings requires that higher standards of quality in manufacturing and inspection of bearings be adopted by the bearing manufacturer. Inspection for mechanical tolerances, raceway and ball surface finish should be supplemented by making sure that the lubricant is very clean and free from foreign particles. It is desirable that grease-lubricated bearings be provided with some type of shielding.

5. The manufacture of grease-lubricated shielded bearings will not obviate the necessity of providing even better packaging, preservation, and handling methods since such bearings will be installed in equipment as received from the bearing manufacturer.

6. A high temperature grease of the MIL-L-3545 type is recommended for use in lubricating the connecting-rod ball bearings of the Air Supply Units BuOrd 417054-1. This grease will greatly extend the time between overhaul of these units.

7. It is recommended that additional lubricants for the Gunar gyros be tested by the manufacturer. The use of diester fluids containing antiwear agents and minor amounts of much less volatile components deserve trial. Also, the possibilities of MIL-G-15793 grease should not be overlooked.

8. A study of the oil absorbing properties of the bearing retainers used in the Gunar gyros should be made and should include an investigation of other materials with oil absorbing properties superior to those of the retainers now used.

9. A means of providing bearing preload of the Gunar gyros which would also incorporate self-alignment features should be studied. This would do much to reduce the extremely close manufacturing tolerances required and might improve bearing behavior.

10. Further research on the use of helium or other inert gases as an atmosphere in which to operate small high-speed gyros is recommended. Particular emphasis should be placed on a study of the effect of these gases on bearing wear and lubricant stability.

11. The use of gyro rotor coast-time data as a means of studying bearing friction has little value unless the rotor speeds are reduced to 900 rpm or below before deceleration tests are made. This is necessary to reduce friction due to windage. The influence of other factors within the bearings at high rotational speeds should be determined with the rotor operating in a vacuum or in a low-density atmosphere.

12. The value of the sound-level meter as an aid in bearing inspection has been established. Much additional information concerning bearing noise characteristics as related to bearing and lubricant condition will be obtained by analyzing the noise with an instrument similar to the Panoramic Sonic analyzer. It is recommended, however, that transducers which have a frequency response range covering at least the audio-frequency spectrum be selected. Small barium titanate accelerometers similar to the one used in the current study have proven satisfactory. The use of sound-level meters and analyzers at key gyro overhaul stations would do much to eliminate the human element which exists in the present methods of bearing inspection. Further laboratory research, however, should be conducted by operating rotor bearings in special equipment designed

specifically for studies in bearing noise and where resonant vibration of the structure of the test equipment can be controlled.

ACKNOWLEDGMENT

The authors wish to express their appreciation to C. R. Singleterry for his assistance in the examination of the bearings and in the interpretation of the results of this phase of the investigation.

* * *

REFERENCES

1. Romans, J. B., and Brophy, J. E., "Visit of J. E. Brophy and J. B. Romans, NRL, to the Eclipse-Pioneer Division, Bendix Aviation Corporation, Teterboro, New Jersey, and the Sperry Gyroscope Company, Great Neck, New York, to discuss Problems of Gyro Lubrication," NRL Letter Report 3270-232/49 hl to BuOrd, August 9, 1949.
2. Romans, J. B., "Visit of J. E. Brophy and J. B. Romans, NRL, to the Arma Corporation, Brooklyn, New York, to discuss Problems Related to the Development of Improved Lubricants for High Speed Gyros," NRL Letter Report 3270-204A/50 amf to BuOrd, July 11, 1950.
3. Brophy, J. E., and Romans, J. B., "Conference between BuOrd, Codes Rel, Re4c, Re8, and Code 3270, NRL, J. E. Brophy, C. M. Murphy and J. B. Romans to discuss Problems of Gyro Lubrication," Memorandum 3270-18/50 hl to Director, NRL, January 19, 1950.
4. Romans, J. B., "Visit of J. B. Romans, NRL, to the Norfolk Naval Shipyard, Portsmouth, Virginia, and to the Naval Air Station, Norfolk, Virginia, to discuss Problems Related to the Development of Improved Lubricants for Gyroscopes and Optical Instruments," NRL Letter Report 3270-183/50 mm to BuOrd, June 29, 1950.
5. Romans, J. B., and Brophy, J. E., "Visit of J. E. Brophy and J. B. Romans, NRL, to the U. S. Naval Base, Philadelphia, Pa., to discuss Problems Related to the Development of Improved Lubricants for Gyroscopes," NRL Letter Report 3270-119/50 hl to BuOrd, May 3, 1950.
6. Romans, J. B., "Conference between Mr. W. Krupick, Kearfott Company, Inc., New York, and J. B. Romans, Code 3270, NRL, to discuss Problems of Gyro Lubrication," NRL Letter Report 3270-365A/50 bcf to BuOrd, November 21, 1950.
7. Brophy, J. E., and Romans, J. B., "The Lubrication of High-Speed Gyros," NRL Report 3840, August 3, 1951.
8. Brophy, J. E., and Romans, J. B., "The Lubrication of Gyroscopes," Transactions of the ASME, 1147-1152, August 1953.
9. Informal Memo from BuOrd Code Re4c, "Gyro Mark 31 Operating Conditions."
10. Navy Bureau of Ordnance Specification 14-0-20, "Oil, Lubricating, Instrument (Synthetic)," December 10, 1946.
11. Military Specification MIL-G-15793, "Grease, Instrument," (Superseding Specification (ORD) 14-G-3), November 1, 1950.
12. Baumzweiger, B., "Application of Piezoelectric Vibration Pick-ups to Measurement of Acceleration, Velocity, and Displacement," J. Acoust. Soc. Am. 11: 303-307 (1940).
13. Fleming, L., "A Miniature Barium Titanate Accelerometer," Nat. Bur. Stds. Report 1094, November 26, 1951.

14. Buhl, W. T., "Ball Bearing Noise and Vibration," J. Acoust. Soc. Am. 13: 51-53 (1941).
15. Romans, J. B., "Visit of J. B. Romans and T. M. Thomas, NRL, to the Norfolk Naval Shipyard, Portsmouth, Virginia, to discuss Problems Related to the Development of Improved Lubricants for Gyroscopes and Optical Instruments," NRL Letter Report 3270-91A/52 ech to BuOrd, March 3, 1952.
16. Military Specification MIL-L-3545, "Lubricating Grease: High Temperature," (Superseding Specification AN-G-5a), July 25, 1951.
17. Brophy, J. E., Larson, J., Singleterry, C. R., Zisman, W. A., "High Temperature Lubrication of Electric Motor Ball Bearings," NRL Report 3971, November 28, 1952.
18. Gothberg, E., "How to Retain the Original Precision in Ball and Roller Bearings," Microtecnic 5 (No. 6): 395-403 (1951).
19. Pichaud, M., "Use and Manufacture of High-Precision Antifriction Bearings," Microtecnic, 5 (No. 6): 368-386 (1951).
20. Jones, A. B., "The Life of High-Speed Ball Bearings," Transactions of the ASME, 74: 695-703, July 1952.
21. Getzlaff, G., "The Behavior of Rolling Bearings at Very High Running Speeds," The Engineer's Digest, 13 (No. 11): 379-384, November 1952.
22. Jones, F. C., and Wilcock, D. F., "The Mechanism of Lubrication Failure in High-Speed Ball Bearings," Transactions of the ASME, 72: 817-823, August 1950.

* * *

| | | | |
|---|---|--|--|
| <p>UNCLASSIFIED</p> <p>Naval Research Laboratory. Report #291. SYNTHETIC LUBRICANTS FOR GYROSCOPES, by J. B. Romans and T. M. Thomas. 39 pp. & figs., February 4, 1958.</p> <p>The failure of many types of Naval gyroscopes while in service or after being taken from storage has been due to rotor bearing failures. A project was established to develop improved lubricants for Naval gyroscopes and to reduce the number of proprietary lubricants to one or two. The Naval gyroscopes investigated included those from the electrically driven Gun Sight Mark 20 and Stable Element Mark 6, the air-driven gyros from the Gun Sight Mark 15 and the Guner Mark 31 0.1 Fg 2 gyro. Measurements were made of bearing temperatures, rotor speed, rate of deceleration, power input, and bearing noise level; and the noise components were analyzed. Both Specification 1A-0-20 oil and MIL-G-15793 instrument grease adequately lubricated the two Gun Sight Mark 20 gyros. These lubricants were also suitable for the Stable Element Mark 6 gyro, but satisfactory use of the oil required that the level in the lower reservoir be higher than that required for the proprietary lubricant. Gyros from the three Gun Sights Mark 15 were operated with Specification 1A-0-20 oil, MIL-G-15793 instrument grease, and an experimental copper phthalocyanine-diester grease. The 1A-0-20 oil and</p> <p>UNCLASSIFIED (over)</p> | <p>UNCLASSIFIED</p> <p>Naval Research Laboratory. Report #291. SYNTHETIC LUBRICANTS FOR GYROSCOPES, by J. B. Romans and T. M. Thomas. 39 pp. & figs., February 4, 1958.</p> <p>The failure of many types of Naval gyroscopes while in service or after being taken from storage has been due to rotor bearing failures. A project was established to develop improved lubricants for Naval gyroscopes and to reduce the number of proprietary lubricants to one or two. The Naval gyroscopes investigated included those from the electrically driven Gun Sight Mark 20 and Stable Element Mark 6, the air-driven gyros from the Gun Sight Mark 15 and the Guner Mark 31 0.1 Fg 2 gyro. Measurements were made of bearing temperatures, rotor speed, rate of deceleration, power input, and bearing noise level; and the noise components were analyzed. Both Specification 1A-0-20 oil and MIL-G-15793 instrument grease adequately lubricated the two Gun Sight Mark 20 gyros. These lubricants were also suitable for the Stable Element Mark 6 gyro, but satisfactory use of the oil required that the level in the lower reservoir be higher than that required for the proprietary lubricant. Gyros from the three Gun Sights Mark 15 were operated with Specification 1A-0-20 oil, MIL-G-15793 instrument grease, and an experimental copper phthalocyanine-diester grease. The 1A-0-20 oil and</p> <p>UNCLASSIFIED (over)</p> | <p>1. Synthetic lubricants</p> <p>2. Gyroscopes - Lubrication</p> <p>I. Romans, J. B.</p> <p>II. Thomas, T. M.</p> | <p>1. Synthetic lubricants</p> <p>2. Gyroscopes - Lubrication</p> <p>I. Romans, J. B.</p> <p>II. Thomas, T. M.</p> |
| <p>UNCLASSIFIED</p> <p>Naval Research Laboratory. Report #291. SYNTHETIC LUBRICANTS FOR GYROSCOPES, by J. B. Romans and T. M. Thomas. 39 pp. & figs., February 4, 1958.</p> <p>The failure of many types of Naval gyroscopes while in service or after being taken from storage has been due to rotor bearing failures. A project was established to develop improved lubricants for Naval gyroscopes and to reduce the number of proprietary lubricants to one or two. The Naval gyroscopes investigated included those from the electrically driven Gun Sight Mark 20 and Stable Element Mark 6, the air-driven gyros from the Gun Sight Mark 15 and the Guner Mark 31 0.1 Fg 2 gyro. Measurements were made of bearing temperatures, rotor speed, rate of deceleration, power input, and bearing noise level; and the noise components were analyzed. Both Specification 1A-0-20 oil and MIL-G-15793 instrument grease adequately lubricated the two Gun Sight Mark 20 gyros. These lubricants were also suitable for the Stable Element Mark 6 gyro, but satisfactory use of the oil required that the level in the lower reservoir be higher than that required for the proprietary lubricant. Gyros from the three Gun Sights Mark 15 were operated with Specification 1A-0-20 oil, MIL-G-15793 instrument grease, and an experimental copper phthalocyanine-diester grease. The 1A-0-20 oil and</p> <p>UNCLASSIFIED (over)</p> | <p>UNCLASSIFIED</p> <p>Naval Research Laboratory. Report #291. SYNTHETIC LUBRICANTS FOR GYROSCOPES, by J. B. Romans and T. M. Thomas. 39 pp. & figs., February 4, 1958.</p> <p>The failure of many types of Naval gyroscopes while in service or after being taken from storage has been due to rotor bearing failures. A project was established to develop improved lubricants for Naval gyroscopes and to reduce the number of proprietary lubricants to one or two. The Naval gyroscopes investigated included those from the electrically driven Gun Sight Mark 20 and Stable Element Mark 6, the air-driven gyros from the Gun Sight Mark 15 and the Guner Mark 31 0.1 Fg 2 gyro. Measurements were made of bearing temperatures, rotor speed, rate of deceleration, power input, and bearing noise level; and the noise components were analyzed. Both Specification 1A-0-20 oil and MIL-G-15793 instrument grease adequately lubricated the two Gun Sight Mark 20 gyros. These lubricants were also suitable for the Stable Element Mark 6 gyro, but satisfactory use of the oil required that the level in the lower reservoir be higher than that required for the proprietary lubricant. Gyros from the three Gun Sights Mark 15 were operated with Specification 1A-0-20 oil, MIL-G-15793 instrument grease, and an experimental copper phthalocyanine-diester grease. The 1A-0-20 oil and</p> <p>UNCLASSIFIED (over)</p> | <p>1. Synthetic lubricants</p> <p>2. Gyroscopes - Lubrication</p> <p>I. Romans, J. B.</p> <p>II. Thomas, T. M.</p> | <p>1. Synthetic lubricants</p> <p>2. Gyroscopes - Lubrication</p> <p>I. Romans, J. B.</p> <p>II. Thomas, T. M.</p> |